CHALLENGES AND OPPORTUNITIES FOR THE EU COMMON FISHERIES POLICY APPLICATION IN THE MEDITERRANEAN AND BLACK SEA

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CHALLENGES AND OPPORTUNITIES FOR THE EU COMMON FISHERIES POLICY APPLICATION IN THE MEDITERRANEAN AND BLACK SEA

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Fishing has several implications that go far beyond the action of taking fish out of the sea.
Image: Meltem Ok.

The application of the Common Fisheries Policy (CFP) in the Mediterranean and Black Sea faces several challenges also because of large ecological, economic, political and institutional differences across the basin. The challenge of CFP application is exacerbated by the legal/administrative situation, with large areas outside national/EU jurisdictions, by the different development of fisheries that result in fleet capacities highly different on opposite shores of some sub-basins, as well as by uneven monitoring and data availability across the basins that result in situations that haper sustainable management. This book collates analyses related to the application of the principles included in the CFP in Mediterranean and Black Sea, including assessments of current status, scenario analyses, visions of best solutions, evaluation of critical hot spots and effects of regionalization of fisheries management. The eBook tackles from local to transboundary issues and solutions and provides a broad vision of problems together with important practical solutions for CFP application in the Mediterranean and Black Sea.

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Editorial: Challenges and Opportunities for the EU Common Fisheries Policy Application in the Mediterranean and Black Sea

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Editorial on the Research Topic

Challenges and Opportunities for the EU Common Fisheries Policy Application in the Mediterranean and Black Sea

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INTRODUCTION

Fishing in the Mediterranean and Black Sea has always been a key economic activity providing livelihood opportunities for hundreds of thousands of people and shaping the culture of the region's coastal communities (Farrugio et al., 1993; Coll et al., 2010; FAO, 2016). From mid 1990s to 2010s, total reported landings fluctuated around 1 million and 500,000 t per year for the Mediterranean and Black sea, respectively (**Figure 1**). However, landings dropped to 817,000 and 265,000 t in 2014 in the Mediterranean and Black sea respectively (FishstatJ, GFCM capture production Dataset), while the total value of fish landings was estimated to be at a minimum, around 3.1 billion USD (FAO, 2016).

The negative trends in landings are worrying signals of a critical situation. About 85% of assessed stocks are fished at biologically unsustainable levels (FAO, 2016), and the overall level of overfishing is around 2–3 times F_{MSY} (European Commission, 2016). The reasons behind these critical conditions are not solely linked to the intense fishing but to the increasing cumulative pressures of a wide range of human stressors that include also aquaculture activities, pollution, habitat degradation, biodiversity loss, and tourism (Coll et al., 2010; Colloca et al., 2013; Piroddi et al., 2017). Climatic induced changes and invasive species are also posing additional threats to exploited marine resources (Libralato et al., 2015; Vasilakopoulos et al., 2017).

There are examples of Mediterranean fisheries exploiting stocks at rates consistent with Maximum Sustainable Yield (MSY; e.g., tuna fisheries) and several fishing fleets are showing important reduction in their capacity (European Commission, 2016; EU Fleet Register). However, the general situation is widely recognized as worrisome and the reduction of fishing mortality—in particular for demersal species—toward a MSY reference value (F_{MSY}) needs to be combined with a substantial change in fisheries selectivity in order to maximize stock biomass, fisheries yield and revenues (Colloca et al., 2013; Vasilakopoulos et al., 2014). Despite recent improvements in

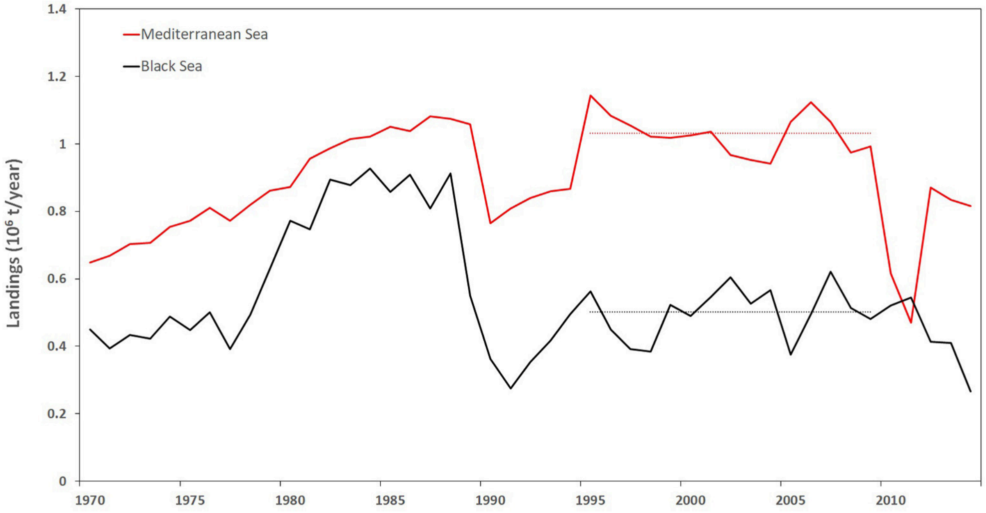

FIGURE 1 | Time series of official landings for the Mediterranean and Black Sea (data from FAO-GFCM Capture fisheries Dataset). Dotted lines indicate the average landings for the period 1995–2009.

the number of stock assessments (GFCM, 2016; STECF, 2016), the number of fish stocks with unknown status remains large (European Commission, 2016), with the possibility that the negative evidences of quantitative stock assessments represent just the tip of the iceberg. With the exception of tuna fisheries, no quotas or total allowable catch (TAC) have been established in the area because of political resistance of the Member States partly motivated with the multi-species nature of the fisheries that are therefore regulated through technical measures and by control of the fleet capacity as proxy of fishing effort (Villasante and Sumaila, 2010; Da Rocha et al., 2012; Carpenter et al., 2016). Furthermore, the widespread small-scale fisheries and the unquantified recreational fisheries are often arguments for high uncertainty on assessments and the difficulties to control and manage Mediterranean and Black Sea wild resource exploitation (Gascuel et al., 2014; Hyder et al., 2017; Piroddi et al., 2017; Selig et al., 2017).

In this context, the application of the Common Fisheries Policy (CFP) in the Mediterranean and Black Sea faces several challenges also because of large ecological, economic, political, and institutional differences across the basin. The challenge of CFP application is exacerbated by the legal/administrative situation, with large areas outside national/EU jurisdictions, by the different development of fisheries that result in fleet capacities highly different on opposite shores of some sub-basins, as well as by uneven monitoring and data availability across the basins that result in situations that hamper sustainable management (Coll et al., 2010; Colloca et al., 2013; Vasilakopoulos et al., 2014; Piroddi et al., 2017).

The latest European Union CFP reform (EC Regulation N° 1380/2013) aims at implementing a community system for conservation of marine fishery resources and for the management of fisheries exploitation in order to guarantee ecological, economic, and social sustainability. These objectives are also a high priority of many national and international regulations and initiatives [e.g., European Marine Strategy Framework Directive (MSFD; 2008/56/EC); Convention of Biological Diversity (CBD), Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), United Nations Sustainable Development Goals (SDGs)] which aim to promote the preservation of natural ecosystems and a sustainable use of fishery resources (Piroddi et al., 2017).

Considering past experiences and failures, the CFP envisages the application of the precautionary principle (Garcia, 1995) and the progressive implementation of an ecosystem-based approach for fisheries management (EAFM, Garcia and Cochrane, 2005), through a series of activities that include adoption of conservation measures, delineation of multiannual plans, reduction of unwanted catches through landing obligation, regionalization of the CFP, transferable fishing concessions, and promotion of sustainable aquaculture. Overall, the CFP should ensure that, by 2020 at the latest, fishing mortality rates are set to levels which will rebuild or maintain stocks above biomass levels that could produce the MSY also on the basis of best scientific advice, data collection, and financial supports (EC Regulation 1380/2013). To cover research gaps and current challenges, this Special Issue compiles new empirical evidence and policy recommendations on how scientific outcomes can better inform management decisions in order to create new windows of opportunities to navigate into new sustainable trajectories.

Based on findings from the 16 papers included in this Special Issue, we provide an overview of the main lessons learned and key recommendations for scientists, policy-makers, and practitioners who intend to operationalize the application of the CFP in the Mediterranean and Black sea. We have organized the content of the Special Issue in three thematic areas: (i) trends and ecosystem impacts of fishing activities, (ii) fisheries management, technical measures and participatory approaches implemented under the CFP, and (iii) current and future challenges toward the application of the CFP.

THE COMMON FISHERIES POLICY IN THE MEDITERRANEAN AND BLACK SEA

Trends and Ecosystem Impacts of Fishing Activities

The first thematic area contains reviews of the state of exploited ecosystems and stocks in the Mediterranean (Colloca et al.; Cardinale et al.) and Black Sea (Oguz), as well analyses including socio-economic fisheries aspects (Sabatella et al.; Raykov and Duzgunes) and physical oceanographic drivers (Guraslan et al.). Colloca et al. carried out a comprehensive review focused on the recent data on Mediterranean fishing fleets and landings, results from stock assessments and ecosystem models, as well as information on invasive species, to provide a diagnosis of the state of resources in different Mediterranean geographical sub-areas. The authors conclude that the current knowledge on fisheries and ecosystems presents a worrisome picture where the effects of poorly regulated fisheries, in combination with growing climate change impacts and the expansion of non-indigenous species, are rapidly changing the structure and functioning of the ecosystem with unpredictable effects on the goods and services provided.

Cardinale et al. analyzed all available stock assessments and effort data for the most important commercial species and fleets in the Mediterranean Sea. The synthesis shows that observed reduction of fishing effort did not result in reduction of fishing mortality. Key reasons for the lack of relationship between nominal effort and fishing mortality for all commercial species can be found in the ineffectiveness of the current effort control system, the continuous non-adherence of adopted management measures to the scientific advice and the inadequacies of existing national management plans. The authors undoubtedly recommend that alternatives management measures as a TAC based system are necessary in the Mediterranean Sea if the EU is willing to move toward the achievement of the CFP's objectives before 2020.

The economic performance of three important Italian trawl fisheries (Northern Thyrrenian Sea, South of Sicily, Northern Adriatic Sea) presented by Sabatella et al. shows that the nominal fishing effort has decreased remarkably in the last 10 years. The reduction in capacity was promoted by public funding but also by a voluntary departure from the sector due to the general obsolescence of the fishing fleets, the low productivity and the increasing operating costs. In the very last years an increasing trajectory for landings together with the reduction of input costs increased economic profitability of these fisheries. Nevertheless, additional management efforts are needed on an urgent basis in order to ensure the achievement of the management goals defined by the CFP.

The overview of the multiple stressors (e.g., eutrophication, alien species invasions, natural climatic variations) presented in Oguz shows the critical state of important fish stocks in the Black Sea. In this ecosystem, perturbed and degraded since the 1970s, nearly all commercially important fish stocks have been severely depleted due to decades of unsustainable exploitation resulting from excessive fishing capacity and inappropriate fishing practices. The study highlights that the fisheries management and efforts devoted to the rehabilitation from long-term chronic degradation of the food web structure need to be carried out altogether as a part of a comprehensive ecosystem-based management strategy.

The lack of bio-economic studies and common fisheries management plans to control overexploitation and unknown use of the resources in the Black Sea are further emphasized in Raykov and Duzgunes. According to the authors, the future of fisheries management in Black Sea is intrinsically linked with the setting of cross-sectoral policies deal with the cumulative impact of human activities, thus including the Maritime Policy and the MSFD. Under this context, the public and industry are more inclined to support measures upon which they have been consulted, so public participation at the implementation phase is critical.

The potential influence of interannual and seasonal variability of temperature and surface currents, as well as the effect of migration on the success of anchovy overwintering for both the Black and Azov Sea is analyzed in Guraslan et al. by using a Lagrangian modeling approach. Results show that the intensity and timing of autumnal cooling, coupled with current strength, can be of significant importance in determining annual and seasonal variability of migration success of anchovy thus affecting the dynamics of this important commercial species in the Black Sea.

Fisheries Management, Technical Approaches, and Participatory Approaches Implemented Under the CFP

A set of papers exemplify the potential of different quantitative tools (Quetglas et al.; Russo et al.), of spatial and technical measures (Pérez-Ruzafa et al.; Tsagarakis et al.), as well as of participatory approaches (Lembo et al.; Bastari et al.) in supporting fisheries management.

The application of the EAFM for the bottom trawl and small-scale fisheries in the Balearic Islands (Quetglas et al.) highlights that despite the fishing effort of the bottom trawling has remained relatively low compared to nearby areas, fishing exploitation has produced negative effects on the main demersal resources by altering populations' resilience and by increasing their sensitivity to the climate variability. Quetglas et al. also show that the availability of reliable data is still a challenge because sales outside the official market are important for species with high commercial value. This result reinforces the need to sensitize fishermen about the importance of providing the best data possible—including those for recreational fisheries—to scientists in order to help improving the stock assessment and management.

Russo et al. used a wide set of individual vessel data, including Vessel Monitoring System (VMS), integrated and compared with overall commercial data, for developing a dynamic spatial assessment for European hake, red mullet, giant red shrimp, and deep-water rose shrimp fisheries in the Ionian Sea. The approach allowed to identify main fishing grounds and to apply the bioeconomic modeling tool (BEMTOOL) whose scenarios highlighted that significant improvements in the exploitation pattern could be achieved by setting up spatial and/or temporal gear-specific bans of the fishing activity, and in particular a 3-month fishing ban for trawlers.

Pérez-Ruzafa et al. made a comparative analysis of specific characteristics and effectiveness of Marine Protected Areas (MPAs) between the North East Atlantic and the Mediterranean Sea. The paper highlights that an optimal management strategy for designing an MPA to protect biodiversity and sustain fishing yields consists of a multi-zoning scheme obtained by combining a network of no-use areas with fished boxes. The study advocates for an optimum size of no-take zones that would range between 600 and 1,500 ha and considers that the spill-over effects on fisheries improves when the distance between MPAs is within a few tens of kilometers.

The implementation of a landing obligation, a key element of the recent reform of the EU CFP [Regulation (EU) N° 1380/2013], is the focus of Tsagarakis et al. that synthesized the available records of discards in the Mediterranean bottom trawl fisheries. The authors found high discard ratios for 15 species (9 bony fishes, three crustacean decapods, and three elasmobranchs), but important target species such as hake, red mullets and highly commercial shrimps showed generally low discard ratios. The authors also highlight that discards for a given commercial species are likely to fluctuate within a fishery, across seasons, years, and regions.

The role of participatory methods and expert consultations' approaches in the assessment of fishery resources is a result of the paper by Lembo et al. The authors explored stakeholders' perception of the objectives and indicators used in the Northern Mediterranean Sea for the monitoring and assessment of ecosystems and marine fishery resources, as well as the stakeholder preferences on alternative management options for improving fishery sustainability. Lemboet al. showed that understanding and incorporating stakeholders' knowledge and views could successfully contribute to effective fisheries management by possibly increasing legitimacy, credibility, and compliance to the EU's CFP.

Local ecological knowledge (LEK) was used in Bastari et al. to understand how benthic invertebrates species have changed in abundance in the central Adriatic Sea since the 1980s. The bryozoan *A. semiconvoluta* is the only invertebrate species that, based on the fishers' perception, had an increasing trend in the last 40 years with no significant differences between coastal and offshore areas. These results represent a useful example of how LEK provides an opportunity to fill current knowledge gaps when conventional fisheries management assessment method does not provide enough data.

Current and Future Challenges Toward the Application of the CFP

The last thematic area contains reviews and analyses on the fisheries management systems for Mediterranean (Vielmini et al.; Carpi et al.) and Black Sea (Salihoglu et al.), also in relation with other regulations (Raicevich et al.).

Multiannual management plans (MAPs) are key tools for restoring and managing fish stocks under the CFP, but the review provided by Vielmini et al. shows that such plans have not yet been generally established in EU Mediterranean waters. Despite the fact that policy tools providing frameworks to halt overfishing were already in place during the past two decades (i.e., UNCLOS, FAO Code of Conduct, 2002 CFP), they have been disregarded in the Mediterranean Sea due to lack of implementation and enforcement. Although isolated and not yet enforced, the newly adopted MAP in the Strait of Sicily represents a significant advance.

Carpi et al. synthesized the improvements, flaws and difficulties that have characterized fisheries management in the Mediterranean Sea in the past decade by using anchovy, sardine and Norway lobster fisheries in the Adriatic Sea as example. The authors advocate for the need to adequate assessment models and data, to have regular external review of assessments and to shift from effort control to a quota system in order to align Mediterranean management with the CFP and achieve MSY targets. Moreover, the coordination and role definitions between the General Fisheries Commission for the Mediterranean, the European Commission Directorate-General for Maritime Affairs and Fisheries, the Scientific, Technical and Economic Committee for Fisheries and the Joint Research Centre need to be strongly improved (Carpi et al.).

Salihoglu et al. carried out a quantitative scientific advice on the application of the EU CFP in the Black Sea by analysing the last 15 years and projecting fish stocks under different future climate change scenarios until 2020. Results indicate that the rebuilding of some forage stocks such as anchovy and sprat might not be sufficient to allow for predators like horse mackerel, bonito and bluefish to recover because fishing mortality has stronger impact than food web interactions. Therefore, exploitation levels should be reduced significantly for all species but especially for the piscivorous fish and anchovy for the long-term sustainability of Black Sea fisheries.

The alignment between the Marine Strategy Framework Directive (MSFD) and the CFP is analyzed by Raicevich et al. MSFD criteria and methodological standards were interpreted and applied differently across member States. Therefore authors found lack of coherence in the early implementation of the MSFD, as well as inconsistency in the selection of stocks, application of reference points, and definition of Good Environmental Status. The analysis shows that subregional and regional coordination was not effectively enforced, reducing the likelihood of achieving CFP targets in the Mediterranean by 2020.

CONCLUSIONS

The contributions of this Special Issue, illustrate that there are still critical problems, which undermine the potential recovery of fish stocks in the Mediterranean and Black Sea. Stocks and ecosystems show signs of critical conditions (Cardinale et al. Colloca et al.; Oguz) andeconomic metrics indicate difficulties within the sector (Sabatella et al.). Mixed fisheries of the Mediterranean and Black sea suffer from highly variable discarding practices, whose analysis, however, highlight areas of possible intervention (Tsagarakis et al.).

There is an increasing adoption of updated assessments tools in the area (Quetglas et al.; Cardinale et al.; Carpi et al.) as well as novel quantitative approaches that might provide guidance for evaluating whole ecosystem management options (Salihoglu et al.; Russo et al.; Guraslan et al.). The establishment of MPAs resulted as a valuable tool that might integrate conservation, management and exploitation (Pérez-Ruzafa et al.). Furthermore, data availability is improving and new approaches allow exploiting novel and old information useful to assess and give contribution for the advice (Lembo et al.; Bastari et al.).

Nevertheless, still the acceptance, application and enforcement of regulations seems a problem in the Mediterranean and Black Sea basins (Vielmini et al.; Carpi et al.; Rykov and Duzgunes). Although EU regulations such as CFP and MSFD are possibly converging in goals, their application is clearly jeopardized in the Mediterranean and Black Sea (Raicevich et al.). Overall, the complex social, economic, political, and ecological context of the basin require additional efforts to integrate data across areas and disciplines, to connect people through active participation and stakeholder engagement, and to integrate regulations to define cross-sectoral policies. In spite of the worrying signals for the situation of marine resources in the Mediterranean and Black Sea, which are exacerbated by several stressors and impacts, not solely fisheries, there are also a series of positive evidences and opportunities. Examples of good practices are emphasized in these contributions altogether suggest a complex set of actions that might work.

These papers also provide a useful contribution for the scientific community, fishing industry and policy makers to jointly address both the challenges and windows of opportunities to create plausible sustainable trajectories over the next decade.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Recent Trends and Impacts of Fisheries Exploitation on Mediterranean Stocks and Ecosystems

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This review focuses on the recent data on Mediterranean fishing fleets and landings, results from stock assessments and ecosystem models to provide an overview of the multiple impacts of fishing exploitation in the different Mediterranean geographical sub-areas (GSAs). A fleet of about 73,000 vessels is widespread along the Mediterranean coasts. Artisanal activities are predominant in South Mediterranean and in the eastern basin, while trawling features GSAs in the western basin and the Adriatic Sea. The overall landings of fish, crustaceans and cephalopods, after peaking during mid 90s at about one million tons, declined at about 700,000 tons in 2013. However, while landings are declining in EU countries since the 90s, in non-EU countries a decreasing trend was observed only in the last 5–10 years. The current levels of fishing effort determine a general overexploitation status of commercial stocks with more than 90% of the stock assessed out of safe biological limits. Indicators obtained from available ecosystem models were used to assess the sustainability of the fisheries. They included primary production required to sustain fisheries (PPR), mean trophic level of the catch (mTLc), the loss in secondary production index (L index), and the probability of the ecosystem to be sustainably exploited (p_{sust}). In areas exploited more sustainably (e.g., Gulf of Gabes, Eastern Ionian, and Aegean Sea) fishing pressure was characterized by either low number of vessels per unit of shelf area or the large prevalence of artisanal/small scale fisheries. Conversely, GSAs in Western Mediterranean and Adriatic showed very low ecosystem sustainability of fisheries that can be easily related with the high fishing pressure and the large proportion of overfished stocks obtained from single species assessments. We showed that the current knowledge on Mediterranean fisheries and ecosystems describes a worrisome picture where the effect of poorly regulated fisheries, in combination with the ongoing climate forcing and the rapid expansion of non-indigenous species, are rapidly changing the structure and functioning of the ecosystem with unpredictable effects on the goods and services provided. Although this would call for urgent conservation actions, the management system implemented in the region appears too slow and probably inadequate to protect biodiversity and secure fisheries resources for the future generations.

Keywords: Mediterranean, fisheries, overexploitation, ecosystem models, fisheries management

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INTRODUCTION

The Mediterranean ecosystem has a long history of human disturbance and exploitation. A growing body of knowledge and recent single species assessments are showing a general overexploitation status of commercial fish and shellfish stocks along with a rapid decline of large predators, such as sharks (Ferretti et al., 2008, 2013; Fortibuoni et al., 2010, 2016). While the impact of poorly regulated fisheries is widely documented in EU Mediterranean waters (Colloca et al., 2013; Vasilakopoulos et al., 2014), the status of fisheries and stocks in non-EU countries, where a standardized fisheries data collection system is generally not yet fully enforced, is still unclear. However, taking into consideration the recent reports of the working groups on stock assessment of the General Fisheries Commission for the Mediterranean (GFCM), it is possible to argue that also in the non-EU countries the situation might be critical (GFCM, 2016a,b).

In recent years there are also increasing evidences on the negative impacts of fishing on the Mediterranean trophic web and ecosystem. Analyses on the impact of fishing on the ecosystem, quantified through an index of Loss in secondary production (Libralato et al., 2008) resulted a general low probability of the ecosystem to be sustainably fished in the Mediterranean Sea both from models and data (Libralato et al., 2005). Moreover, the meta-analysis of Mediterranean model outputs highlighted detectable signs of impacts of fishing from several ecosystem indicators (Coll and Libralato, 2012).

The ecosystem change was so fast during the last 50 years to be directly witnessed in different Mediterranean areas by fishermen and vessel captains (Maynou et al., 2011), highlighted from analysis of landing statistics (Fortibuoni et al., 2017), and documented in several studies (Lleonart, 1993; Abelló et al., 2002; Coll et al., 2006, 2007; Libralato et al., 2008; Azzurro et al., 2011).

In addition, there is a growing concern about the damages on the benthic habitat caused by towed gears such as otter trawls, dredges, beam trawls (Pranovi et al., 2000; Smith et al., 2000; de Juan et al., 2007; De Biasi and Pacciardi, 2008; de Juan and Lleonart, 2010).

The critical situation of commercial stocks rose the concerns also for several factors than alone or in combination with fisheries are contributing to worsening the conditions of marine Mediterranean communities. Increasing body of research is showing fast spreading of new invasive species in the Mediterranean (Lejeusne et al., 2009; Galil et al., 2014; Parravicini et al., 2015) that can have indirect effects on resident communities and fisheries difficult to quantify (e.g., Libralato et al., 2015). Pollution and marine litter are having strong attention because of the several indirect and direct impacts on both stocks and fisheries (Galgani, 2015). Nutrient loads from watershed have been regulated with important changes in the last decades resulting in direct effects on marine coastal area primary productivity and exploited resources (Caddy, 2000; Fortibuoni et al., 2017). Climatic global changes are also influencing Mediterranean marine communities by changing average temperature, productivity and water alkalinity (Lazzari et al., 2012, 2014; Cossarini et al., 2015) with potentially large effects on exploited stocks (Colloca et al., 2014).

Although there is a general concern about the lack of adequate management measures to reverse the ongoing negative trends and drive Mediterranean fisheries toward a sustainable exploitation, the overall picture of the situation of fisheries and ecosystems is still rather confused.

In this review, we used multiple source of information to summarize the current knowledge on commercial demersal fisheries in European and non-European waters. Starting from a review of the fisheries trend we considered the status of commercial stocks in the different Mediterranean FAO-GFCM Geographical sub-areas (GSAs). These data were complemented with information on the outputs of main ecosystem models available in Mediterranean to produce an overview of the overall impact of fishing on the ecosystem. In this perspective, we considered also data on non-indigenous fish species and knowledge on the conservation status of Mediterranean fish from the International Union for Conservation of Nature (IUCN) assessments.

Our main goal was to provide a general overview on Mediterranean fisheries and discuss the multiple effects generated by fishing exploitation, from commercial stocks to the whole ecosystem, in relation to the challenging long-term sustainability objectives of the European Union (*sensu* CFP Reg. no. 1380/2013) and FAO (UN; *sensu* SDG 14, FAO SO2 and the Aichi Targets).

MATERIALS AND METHODS

Fisheries Data

Data available on fishing capacity, as total number of artisanal vessels using fixed gears (e.g., trammel nets, long-lines, traps, etc.), trawlers, purse-seiners, and pelagic trawlers, in each Mediterranean Geographical Sub-Areas (GSAs, **Figure 1**) were obtained from several sources (see **Table 1**). These includes technical reports of both the FAO-GFCM and the Scientific Technical and Economic Committee of the European Commission (STECF-EC), as well as fleet data retrieved from the European vessel register (http://ec.europa.eu/fisheries/fleet/index.cfm) and scientific studies.

Landing data by main group of species (i.e., demersal fish, small-pelagics, elasmobranchs, crustaceans, cephalopods) and area were obtained from the GFCM marine capture production database 1970–2014 (http://www.fao.org/gfcm/data/capture-production-statistics/en/). This was complemented for EU GSAs with data from the JRC database on Mediterranean and Black Sea fisheries (https://stecf.jrc.ec.europa.eu/dd/medbs) as well as Italian data included in Mannini and Sabatella (2015).

Fishing mortality and F_{MSY} values were compiled from stock assessment forms produced by both the GFCM and STECF working groups in stock assessment from 2002 to 2014 and summarized by Cardinale and Scarcella (2017).

Reported landing data in each GSA were contrasted with fleet capacity, calculated as total number of trawl vessels, and dimension of the continental shelf (depth range: 0–200 m). This latter was derived from a depth layer downloaded from Marspec database (http://www.marspec.org/).

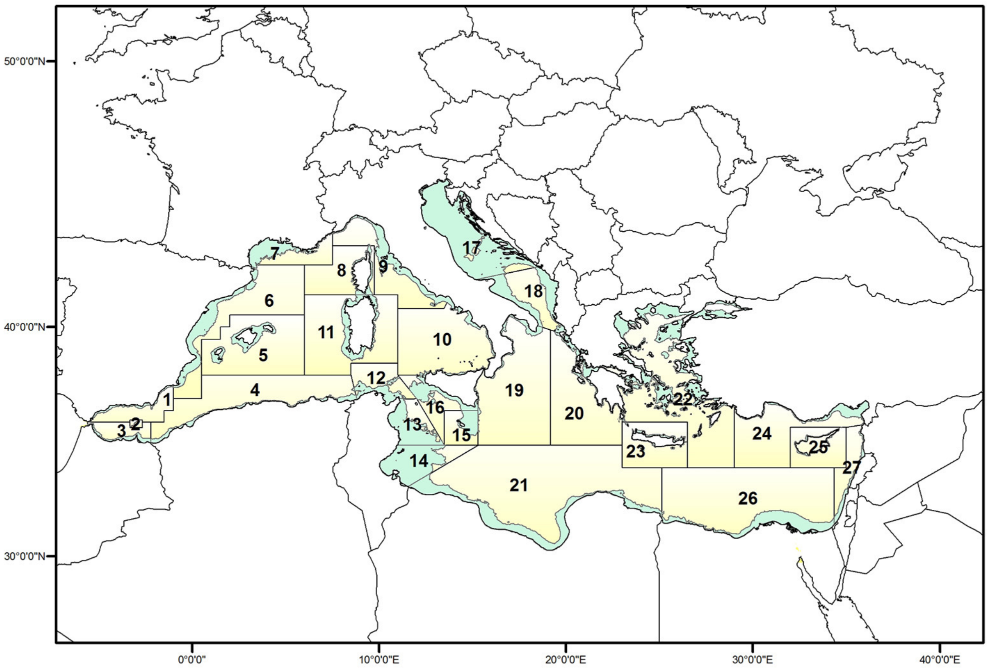

FIGURE 1 | Mediterranean FAO-GFCM Geographical Sub-Areas (GSAs). The continental shelf (0–200 m) is also shown. 1, Northern Alboran Sea; 2, Alboran Island; 3, Southern Alboran Sea; 4, Algeria; 5, Balearic Islands; 6, Northern Spain; 7, Gulf of Lions; 8, Corsica Island; 9, Ligurian and North Tyrrhenian Sea; 10, South Tyrrhenian Sea; 11.1, Sardinia (west); 11.2, Sardinia (east); 12, Northern Tunisia; 13, Gulf of Hammamet; 14, Gulf of Gabes; 15, Malta Island; 16, South of Sicily; 17, Northern Adriatic; 18, Southern Adriatic Sea; 19, Western Ionian Sea; 20, Eastern Ionian Sea; 21, Southern Ionian Sea; 22, Aegean Sea; 23, Crete Island; 24, North Levant; 25, Cyprus Island; 26, South Levant; 27, Eastern Levant Sea.

Ecosystem Indicators

Indicators were obtained from ecosystem models, which are standardized quantitative representations of main biological structure of the ecosystem, from primary producers to top predators. A set of available ecosystem models were selected to fulfill the following aspects: (i) represent substantial parts of each Mediterranean GSA (i.e., the model domain was large enough); (ii) have been well-documented in scientific literature; (iii) were developed for addressing fishing issues, thus they embed detailed description of fisheries landing and discards. The selected ecosystem models, although not available for all GSAs, permit to derive a set of indicators summarizing ecosystem effects of fishing to highlight impact of fishing on ecosystem structure and functioning. In particular we reported total ecosystem biomass (TB), total catches (TC), and the ratio between total catches and primary production (gross efficiency, GE). Moreover, from models were obtained footprint-like measure of fishing pressure, i.e., the primary production required to sustain catches (PPR; Pauly and Christensen, 1995), which together with information on primary production and the mean trophic level of the catches (mTLc; Pauly et al., 1998) provide a framework for assessing status of fisheries (Tudela, 2000; Tudela et al., 2005). These indicators are combined in the Loss in secondary production (L index), an index that allows assessing the ecosystem overfishing level since reference levels in terms of probability of the ecosystem to be sustainably fished (p_{sust}) were empirically defined (Libralato et al., 2008). Such indices collected for the set of available models provide an evaluation of ecosystem status by GSA.

As measures of the possible exposure to the indirect effects of climate change we derived the number of non-indigenous fish species recorded in each GSA. This was summarized from the CIESM Atlas of exotic species in Mediterranean (http://www.ciesm.org/online/atlas/) and complemented with supplementary bibliographic information from specific areas (Katsanevakis et al., 2009; Evans et al., 2015).

RESULTS

Effort and Landings Data by GSA

The Mediterranean fishing fleet is made up by about 72,600 vessels of which 85.5% are artisanal vessels using a variety of gears (e.g., trammel nets, gillnets, longlines, traps, etc.), about 9% are trawlers and 5% purse seiners and pelagic trawlers (**Table 1**, dredges were excluded). Fleet data show major differences across the Mediterranean GSAs. The largest artisanal fleets occur in Tunisia (GSAs 12–14), Aegean Sea (GSAs 22–23), and Northern Adriatic (GSA 17), whilst trawlers are mainly concentrated in Egypt (GSA 26), Adriatic (GSAs 17–18), and Algeria (GSA 4, **Table 1**). In terms of fishing pressure on the shelf, the area with the highest number of artisanal vessels per km^2 are the Levantine Sea (GSA 27), Cyprus (GSA 25), Morocco (GSA 3), Algeria (GSA 4), Eastern Ionian Sea (GSAs 20, **Figure 2A**). A different pattern occurs for trawlers where the

TABLE 1 | Summary of fleet capacity data in 2013 and annual landing data by Mediterranean Geographical-Subareas GSA or combination of GSAs in 2014.

GSA	Country	Total n. fishing vessels	Trawlers	Artisanal vessels	Purse seiners and pelagic trawlers	Total landing (ton)	Landings demersal fisheries (ton)	Landings purse seiners and pelagic trawlers (ton)	Continental shelf surface (km^2, 0–200 m)	References
1	Spain	788	110	588	90	18,894	6,254	12,640	3,925.8	EU fleet register
3	Marocco	2,146	106	1,916	124	31,867	16,048	15,819	4,581.4	FAO, 2016
4	Algeria	4,743	550	2,906	1,287	97,741	41,247	56,494	9,516.7	FAO, 2016
5	Spain	373	63	302	8	2,359.1	1,662.83	696.2	10,877.9	EU fleet register
6	Spain	1,631	496	1,000	135	50,656	15,246	28,529.8	24,529.4	EU fleet register
7	France	1,261	73	1,106	82	14,253	8,938.6	9,641	14,211.4	EU fleet register
8	France	194	9	185	0	355.4	257.8	97.6	4,361.1	EU fleet register
9	Italy	1,622	302	1,277	43	17,296	11,323.5	5,972.1	16,423.4	Mannini and Sabatella, 2015
10	Italy	2,657	247	2,324	86	17,396	11,602	5,794	9,361.9	Mannini and Sabatella, 2015
11	Italy	1,239	130	1,109	0	11,326	11,325	0.52	14,173.5	Mannini and Sabatella, 2015
12–14	Tunisia	11,484	374	10,702	408	11,0882	20,044	90,838	77,991.7	FAO, 2016
15	Malta	1,025	22	999	4	4,780.5	1,040	3,740.5	8,737.0	EU fleet register
16	Italy	1,172	405	728	39	19,824	15,324	4,499.5	14,325.3	Mannini and Sabatella, 2015
17	Italy, Slovenia, Croatia	5,159	1,043	3,788	328	14,9186	43,984.3	10,5201.7	79,315.3	Mannini and Sabatella, 2015; STECF, 2016
18	Italy, Montenegro, Albania	1,605	599	951	55	19,545	13,219	6,325.7	23,670.9	Mannini and Sabatella, 2015
19	Italy	1,568	227	1,319	22	10,140	9,307	599.4	6,729.9	Mannini and Sabatella, 2015
20	Greece	3,553	31	3,482	40	5,051	554	4,497	10,442.3	EU fleet register
21	Libya	4,602	263	4,196	143	25,000	1,600	23,400	54,293.5	FAO, 2016
22–23	Greece	16,526	310	15,931	285	81,661	17,055	62,227	63,069.1	Fleet register; Katağan et al., 2015
24	Turkey	1,839	202	1,577	60	6,773	5,026	1,747	35,427.0	Katağan et al., 2015
25	Cyprus	943	13	928	2	1,218.7	675	543.7	2,773.9	FAO, 2016
26	Egypt	2,989	1,124	1,657	208	61,376	16,944	44,432	32,373.9	FAO, 2016
27	Israel, Lebanon, Syria, Palestine	3,520	39	3,133	348	9,021	1,503	7,518	5,211.8	Levy et al., 2015; FAO, 2016

Total number of fishing vessels (dredges excluded), trawlers, artisanal vessels (e.g., vessels using fixed gears), purse seiners and pelagic trawlers. Landings data are summarized as total landings, landings of demersal fisheries (i.e., trawlers and artisanal vessels) and landings of pelagic fisheries (i.e., purse seiners and pelagic trawlers). The dimension of the continental shelf is also shown.

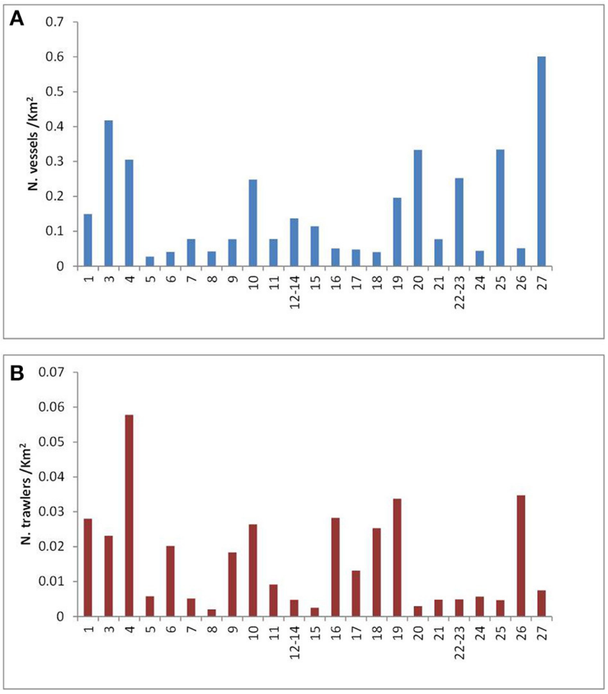

FIGURE 2 | Fishing pressure on the Mediterranean continental shelf, as n. vessel km^{-2}, by GSA and fleet: **(A)** artisanal vessels; **(B)** trawlers (data derived from **Table 1**).

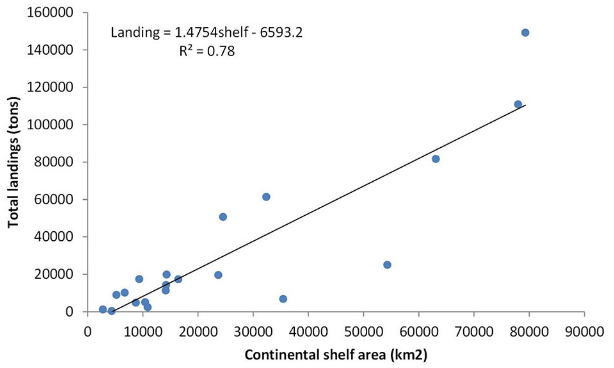

FIGURE 3 | Relationships between the dimension of the continental shelf area of GSAs and the reported total annual landings (GSAs 1-3 are excluded, data shown in **Table 1**).

highest concentration is found in Algeria (GSA 4), Egypt (GSA 26), Western Ionian Sea (GSA 19), Southern Sicily (GSA 16), Southern Adriatic Sea (GSA 18), Northern Alboran Sea (GSA 1) (**Figure 2B**).

The annual landings observed in the different GSAs resulted linearly correlated ($r^2 = 0.78$, $p < 0.01$) with the dimension of the continental shelf (0–200 m depth, **Figure 3**). This appears therefore a key factor in constraining the productivity potential of Mediterranean fisheries.

Temporal Trend in Landings

The estimated total production of demersal and small pelagics species derived from different statitical sources was about 766,600 ton in 2014 similar to the figure that can be obtained from the GFCM capture data (727,000 tons). The landings of demersal species showed large differences among GSAs (**Table 1**): the area with the highest annual production was the Central-North Adriatic (GSA 17) with about 44,000 t, followed by the Algeria's GSA 4 (41,000 t), Tunisian GSAs (20,000 t), Agean Sea and Egypt (about 17,000 t each), Morocco (16,000 t) and finally South of Sicily (14,000 t).

According to the GFCM data, small pelagics (anchovy, sardine and other clupeids) accounted for 333,174 tons while demersal species achieved 394,327 tons. The temporal trend in annual production of demersal fish, crustaceans, cephalopods and small pelagics showed a rapid increase from 70s to the beginning of 90s followed by a declining trend since then. A different picture comes out disaggregating capture data by European (i.e., Spain, France, Italy, Slovenia, Croatia, Montenegro, Albania, Greece, Malta, Cyprus) and non-European countries (i.e., Turkey, Syria, Lebanon, Egypt, Libya, Tunisia, Algeria, Morocco). The reduction trend is determined only by a decreases in the landings of European countries for all the groups but the crustaceans. The landings of non-European countries was featured by a different pattern where a reduction in small pelagics, demersal fish and elasmobranchs occurred only in the last 5–10 years and partially compensated by a continuous increasing in cephalopods and crustaceans landings (**Figure 4**).

Exploitation Status of Commercial Stocks

Data for more than 80 stocks of fish and crustaceans assessed in the period 2002–2014 (**Table 2**) showed that for 90% of them the current fishing mortality (F) is higher than the fishing mortality at MSY (F_{MSY}). The highest F/F_{MSY} values are observed for demersal fish, particularly hake (*Merluccius merluccius*), black bellied anglerfish (*Lophius boudegassa*), and red mullet (*Mullus barbatus*). Most of the assessed stocks of crustaceans and small-pelagics are featured by F/F_{MSY} values between 1 and 2. In general, there are large differences between GSAs in the overexploitation status of species. For example red mulled (*M. barbatus*) appears sustainable exploited in GSAs 10 (South Tyrrhenian) and 18 (South Adriatic) and highly overexploited in GSAs 5 (Balearic) and 11 (Sardinia).

Ecosystem Indicators

Indicators derived from models (**Table 3**) showed large variability in total ecosystem biomass, ranging from 21.31 ton/km^2 in Ionian Sea model to 130 ton/km^2 in Northern Adriatic Sea. There seems to be very poor relationship between total biomass and total catches ($R^2 = 0.0394$). Generally, higher biomasses in the system resulted in lower mTLc. Therefore, PPR% of the catches resulted positively related to total ecosystem biomass ($R^2 = 0.26$). GE was very low for Tyrrhenian and Gulf of Gabes (GE < 0.001) and high for Catalan in the 2000s and Greek Ionian Sea (0.0034 and 0.0040 respectively). Placing PPR% and mTLc in a combined context resulted in systems very likely sustainably fished (Aegean Sea and Gulf of Gabes) in

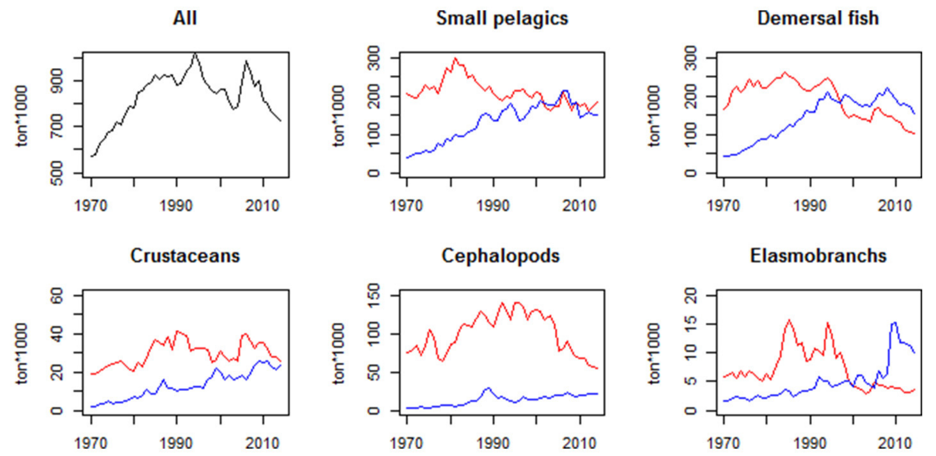

FIGURE 4 | Trend in annual landings of small pelagics, demersal fish, crustaceans, cephalopods, and elasmobranchs in EU (red line) and non-EU (blue line) Mediterranean GSAs. Data were retrieved from the GFCM capture fisheries database (http://www.fao.org/gfcm/data/capture-production-statistics/en/?platform=hootsuite).

contrast to other heavily exploited (Catalan Sea and Adriatic Sea, **Figure 5A**). The quantitative framework provided by Loss in secondary production index and p_{sust} (Libralato et al., 2008) resulted in a very critical situation for most of the exploited areas represented by the ecosystem models (**Figure 5B**). Only Gulf of Gabes, Eastern Ionian, and Aegean Sea were identified as models with sustainable fisheries. Conversely the Adriatic Sea appeared the most critical situation with a probability to be sustainable fished around 20% (**Figure 5B**).

We used the total number of non-indigenous fish species by GSA as an index to exposure to environmental change. The map in **Figure 6** shows main spatial difference among GSAs, with the Eastern basin featured by a high number of new species (94 in Levantine Sea—GSA 27). In contrast, the number of non-indigenous species is low in Central Mediterranean (e.g., Tyrrhenian Sea, Sardinia, Balearic Islands). An intermediate level of non-indigenous species can be found along the African coasts, where new species from the Red Sea and South Atlantic can overlap.

DISCUSSION

There is an increased concern about the status of Mediterranean ecosystem in relation to the sustainability of the current level of fisheries exploitation. Several studies have discussed how the unbalanced fishing in several areas of the Mediterranean is undermining the productivity of both commercial stocks and fisheries activities highlighting the need for a new management strategy aimed at rebuilding overexploited stocks (Colloca et al., 2013; Vasilakopoulos et al., 2014).

However, rarely the impact of fishing has been analyzed at the basin scale and accounting for both the status of the single stocks and the ecosystem. Most of the studies carried out in the last 10 years have focused on EU Mediterranean countries where data of transversal (i.e., catch and effort), biological (i.e., size/age composition of the commercial stocks, biological parameters) and socio-economic indicators are routinely collected on a year basis within the EU-Data Collection Framework (DCF). Since 2008, these data, used to provide advice on the status of the stocks in EU waters within the STECF working groups, have depicted an overall status of overfishing with few exceptions (STECF, 2014, 2016). Although a similar activity has been also developed by the GFCM for stocks in non-EU GSAs, the status of fisheries and stocks in these non-EU areas is less clear due to more scattered data and less commitment in performing standard data collection and stock assessments.

In this study, we revised multiple sources of data on fisheries and stocks from both EU and non-EU GSAs to provide an overall picture of fisheries trends in Mediterranean Sea accounting also for the most relevant effects on the ecosystem.

Spatio-Temporal Trend in Fishing Effort and Landings

Currently, the Mediterranean ecosystem is exploited by about 72,600 vessels most of which (85%) are artisanal boats using many different fishing gears. The artisanal fishing component of the fleet is still extremely important for the socio-economy of many coastal communities other than a source of food, also for representing an important cultural heritage with relevant implication for activities related to the tourism. The main artisanal fleets are concentrated in Aegean Sea (GSAs 22–23); Tunisia (GSAs 12–14), Northern Adriatic (GSA 17), Libya (GSA 21), East Ionian Sea (GSA 20), Algeria (GSA 4), Morocco (GSA 3). The distribution of trawlers indicate that they concentrate mostly in Adriatic GSAs (GSAs 17 and 18), Egypt (GSA 27), Algeria (GSA 4), and North West Spain (GSA 6). Another large component of trawler fleet is located in the Strait of Sicily (GSAs 12–16), where 785 trawlers from Italy, Malta, and Tunisia exploit shared resources also in international waters.

Mediterranean GSAs are however featured by large differences in the dimension of the continental shelf which in turn determine

TABLE 2 | Summary of the most recent F/F_{MSY} ratios available for Mediterranean commercial stocks in the period 2002–2014 (Source: Cardinale and Scarcella, 2017).

		GSAs or combination of GSAs																					
		1	**5**	**6**	**7**	**9**	**10**	**11**	**16**	**17**	**18**	**19**	**20**	**22**	**24**	**25**	**26**	**1–3–4**	**12–16**	**15–16**	**17–18**	**18–19**	**Mean**
Demersal fish	Black-bellied anglerfish		7.39	4.8	3.35																		5.2
	Blackmouth catshark					2.69																	2.7
	Blue whiting	3.5		11.01		1.16																	5.2
	Bogue															3.8							3.8
	Common pandora					1.31														2.4			1.9
	Greater forkbeard					3.16																	3.2
	Hake	9.38	7	5.35	14.91	4.48	5.51	9.47				4.83							6.68		5.56		7.3
	Picarel															0.63							0.6
	Poor cod					1.22																	1.2
	Red mullet		7.64	3.51	1.53	1.17	0.95	9.54		1.82	0.82	2.25			1.3	2.4		4.46		2.89			3.1
	Small-spotted catshark					5																	5.0
	Common sole									1.92													1.9
	Brush tooth lizard fish																2.6						2.6
	Striped red mullet		2.62			1.94											2.7			4.11			2.8
Crustaceans	Spottail mantis shrimp					2.22	2.63			1.31	2.44												2.2
	Norway lobster	1.65	1.76	4.33		2.01					6.32									0.75			2.8
	Giant red shrimp					0.25	1.4	1.61														1.1	1.1
	Blue and red shrimp	3.83	1.28	1.46		1.78	1.55													3.82			2.3
	Peregrine shrimp																2.6						2.6
	Deep-water rose shrimp	1.65	1.1	3.21		1.03	1.35	1.41			2.03	1.63							1.35				1.6
Small pelagics	Anchovy	0.89		1.74		4.87						1.03	1.4	0.94							1.79		1.8
	Sardine	0.89		5		2.11			0.55				1.36	1.07							1.52		1.8

TABLE 3 | Indicators obtained from main ecosystem models developed for large areas of the Mediterranean GSAs.

GSA	Country	Model name	Domain	Surface (km²)	Period	TB (t/km²)	TC (t/km²/year)	PPR%	mTLc	GE (catches/PP)	L index	p_{sust} (%)	References
6	Spain	Southern Catalan Sea	sh+sl	4,500	1976–1980	46.44	3.97	6.35	3.07	0.0025	0.058	50.8 (±17.6)	Coll et al., 2008a
6		Southern Catalan Sea	sh+sl	4,500	1990–2000	58.98	5.36	10.61	3.12	0.0034	0.088	23.1 (±10.9)	Coll et al., 2008a
6		Southern Catalan Sea	sh+sl	4,500	2003	52.64	5.17	7.92	3.11	0.0034	0.067	34.5 (±12.9)	Coll et al., 2008a
7	France	Gulf of Lions	sh+sl	20,400	2000–2009	68.90	2.13	13.58	3.24	0.0020	0.089	23 (±10.8)	Bănaru et al., 2013
8	France												
9	Italy	Central Tyrrhenian Sea	sh+sl	13,785	2007–2010	41.13	0.55	22.20	3.58	0.0007	0.075	30 (±12.5)	Lopez, 2013
12–13–14	Tunisia	Gulf of Gabes	sh	35,900	2000–2005	73.75	1.72	3.77	3.44	0.0010	0.017	92.3 (±7.5)	Hattab et al., 2013
17	Italy	North Central Adriatic	sh	55,500	1975–1980	134.33	3.17	19.44	3.28	0.0028	0.117	19.7 (±9.8)	Coll et al., 2009
17		North Central Adriatic	sh	55,500	mid 1990	130.30	2.45	15.00	3.07	0.0021	0.136	14.3 (±9.1)	Coll et al., 2007
20	Greece	North Eastern Ionian	sh+sl	1,021	1960–1970	44.31	1.03	9.46	3.14		0.075	28.9 (±12.5)	Piroddi et al., 2010
20		Greek Ionian Sea	sh+sl	49,149	1998–2006	21.31	0.60	2.93	2.81	0.0016 0.0030	0.084	59.6 (±16.2)	Moutopoulos et al., 2013
22–23	Greece	North Aegean Sea	sh	8,374	mid 2000	33.04	2.34	6.76	3.47	0.0040	0.028	171.2 (±12.6)	Tsagarakis et al., 2010

Main characteristics of the models are reported, as well as indicators used: TB, total ecosystem biomass; TC, total ecosystem catches (including discards); PPR%, ratio primary production required to sustain fisheries to PP; mTLc, mean trophic level of the catch; GE, gross efficiency (landings/PP); Loss in secondary production index (L index); probability to be sustainably fished (p_{sust}): Domain, model domain (sh, continental shelf; sl, continental slope).

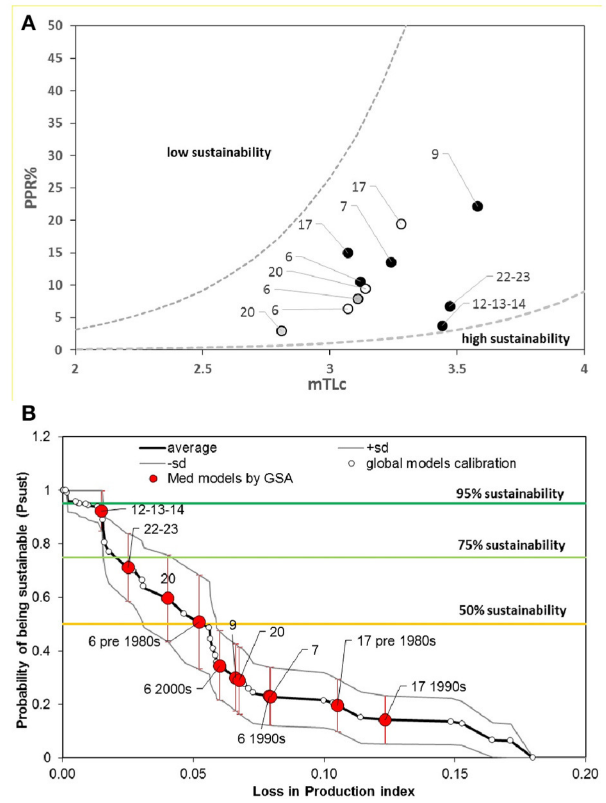

FIGURE 5 | Ecosystem state from the available food web models representing large areas of the GSAs (see **Table 3** for details). **(A)** Primary production required relative to primary production (PPR%) and mean trophic level of the catches for each model; lines divide the plane into regions with different level of sustainability of the fisheries (see Tudela et al., 2005); white dots indicate models representing ecosystems before 1980, gray dots ecosystems between 1980–1999 and black dots food web models of more recent years. **(B)** Quantitative assessment of the probability of the ecosystem to be sustainably fished using the framework provided by Loss in secondary production approach, assuming transfer efficiency as 13.7% (as the modal value for temperate shelfs; Libralato et al., 2008).

also large dissimilarities in fishing pressure (i.e., vessel km^{-2}). Our analysis show that differences in fisheries productivity between different areas can be largely explained by differences in the dimension of the continental shelf, which is thus resulting as one of the most relevant factor constraining fisheries productivity.

Landings data from GFCM capture statistics indicated that the fishing landings of the EU countries declined since mid '90s for the main taxa with the exception of crustaceans, whose landings was substantially stable in the last 30 years. It is worth noting, however, that the catch trend appears completely different in non-EU countries. Here the annual landings of small pelagic and demersal fish species is increasing since 70s and only in the last 5–10 years a decreasing trend is noticeable. Moreover, crustaceans, elasmobranchs, and cephalopods landings are still increasing. The stable or increasing pattern of crustaceans also in EU waters can be the results of a combination of effects, where the ecosystem

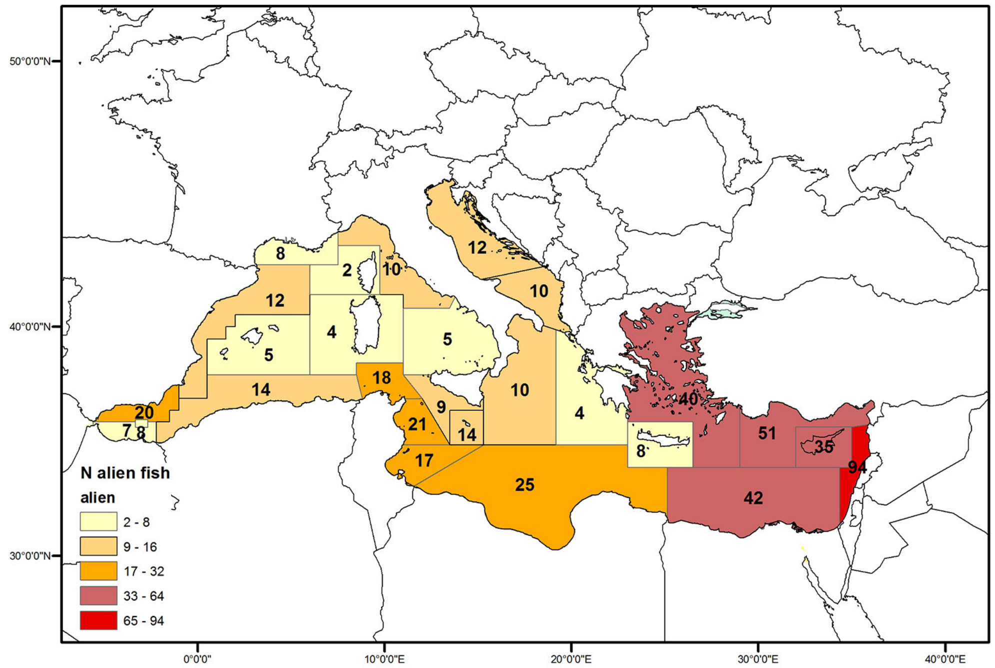

FIGURE 6 | Number of non-indigenous species by GSA. Data from the CIESM Atlas of Exotic Species in the Mediterranean (http://www.ciesm.org/online/atlas/).

change can be one of the most important. Temporal trend of increasing abundance of decapod crustaceans simultaneous with a decreasing of fish has been documented for the bathyal assemblages of the Western Mediterranean (Cartes et al., 2009). In this area, the landings of blue and red shrimp (*Aristeus antennatus*), the main target species of deep trawling, depends also by the climatic condition over the Western Mediterranean (Maynou, 2008). Similarly, the abundance of the deep-water rose shrimp (*Parapenaeus longirostris*), one of the most important commercial shrimp in Mediterranean, is increasing in the Tyrrhenian and Ligurian Seas, with an important effect due to the increasing in water temperature (Ligas et al., 2011; Colloca et al., 2014).

Current increasing landings of crustacean can also result from a sequential overexploitation with trawlers progressively moving from one resource to another in relation to their abundance, profitability and market conditions. Furthermore, a possible role might also by played by a combined effect of predation release, i.e., by the major removal by fisheries of their fish predators (e.g., as detected in N Atlantic; Worm and Myers, 2003), and of scavenging behavior, i.e., their potential advantage on feeding on large amounts of discards produced by Mediterranean fisheries (Tsagarakis et al., 2014). While these aspects need to be furtherly explored, the different temporal catch trends between EU and non-EU GSAs suggest that fishing effort in the two areas has been following an opposite development. Whilst the fishing capacity of European Mediterranean countries decreased in the last 20 years as effects of the decommissioning schemes of the EU with a subsequent reduction in landings, an increasing in fishing capacity cannot be excluded in other Mediterranean areas (Samy-Kamal, 2015).

Impact of Fishing on Commercial Stocks and By-Catch Species

Results of the stock assessments carried out in the last 10 years clearly show that the ongoing fishing pressure is determining a generalized overfishing status of commercial stocks, which appears more relevant for demersal fish. Overfishing is undermining the economic performance of EU Mediterranean fleets, as summarized by the negative trend in economic indicators (e.g., Italian fleets, STECF, 2015), thus making the sector more exposed to the negative effect of the general economic crisis. A negative picture on the effect of poorly regulated fishing activities on Mediterranean fish communities came out also by the assessment done by the International Union for Conservation of Nature (IUCN; Abdul Malak et al., 2011; Nieto et al., 2015) where among the 519 native marine fish species and subspecies assessed in term of conservation status in Mediterranan Sea, 43 species (7.5%) were classified in threatened categories (critically endangered, endangered, or vulnerable). Of this group, 31 species are elasmobranchs making the Mediterranean the region in the world with the higher proportion of threatened species of sharks and rays (Dulvy et al., 2014).

The critical status of elasmobranchs was highlighted by several studies showing a worrisome long term decline (Fortibuoni et al., 2010) accelerated in last decades. For example, pelagic sharks declined by more than 95% during the last century (Ferretti et al., 2008), whilst demersal sharks, such as smooth-hounds (*Mustelus* spp.), disappeared from most of the West Mediterranean in '70s and '80s (Massutí, 1971; Aldebert, 1997; Maynou et al., 2011; Ligas et al., 2013; Fortibuoni et al., 2016; Colloca et al., 2017).

The few geographic sectors where elasmobranchs still show viable populations for local fisheries are those featured by extended continental shelves (e.g., North Adriatic, South Tunisia and Libyan coasts, South of Sicily, and Malta). In these areas the elasmobranchs populations are likely maintained thanks to the occurrence of untrawable areas providing refuge opportunities, a moderate level of fishing intensity (e.g., Turkish coasts, Lybian waters) or a combination of these factors (see Bradai et al., 2012). However, the rapid increasing catches of elasmobranchs in non-EU waters in the last 20 years, shown by the GFCM data (**Figure 4**), can be a worrisome indication of an increased depletion risk for these "residuals" populations.

Impact of Fishing on the Ecosystem

In this study, we made an attempt to summarize the impact of fishing on the ecosystem of different GSAs to understand how much the negative signals derived from single-species models can be also detected at the multispecies level. Although the domain of the ecosystem models never encompassed the whole GSA, the models represented exploited key areas large enough to be considered indicative of the status of the GSA ecosystem, although within GSA there might be areas with contrasting local situations. Synthetic indicators directly derived from models such as total biomass, total catches and mTLc (mean trophic level of the catches) for each ecosystem highlight the difficulties in grasping the ecosystem effects of fishing without considering the productivity and the energetics behind each caught species. For instance the general pattern of higher catches and lower mTLc for ecosystems with higher total biomass (**Table 3**) is related to patterns in the primary productivity across GSAs. This highlight the difficulties for these indicators to detect impacts of fishing, because larger productivity supports ecosystem with heavier exploitation and the lowering of mTLc is simply the result of non-proportional effects of productivity across trophic level. That is why GE, which was suggested as an index of fishing pressure (Christensen et al., 2008), might be misleading in indicating ecosystem overfishing.

Primary production required to sustain catches, instead, accounts for the energy needed to produce caught biomasses at different TL and when scaled to actual PP for obtaining PPR% results in an indicator useful for comparing fishing pressure across ecosystems with very different productivity as the different Mediterranean GSAs. Contrasting PPR% with mTLc using a consolidated framework (Tudela, 2000; Libralato et al., 2005, 2008; Tudela et al., 2005; Coll et al., 2008b), moreover, allows to highlight ecosystem sustainability of fisheries. Areas that resulted exploited sustainably are Gulf of Gabes, as well as Eastern Ionian and Aegean Sea with probability to be sustainably fished (p_{sust}) of 92.3% (±7.5), 59.6% (±16.2%), and 71.2% (±12.6%), respectively. The high sustainability of fisheries in these areas is coherent with fishing pressure characterized by low number of vessels per unit of shelf area for Tunisia and for the large prevalence of artisanal/small scale fisheries in GSA 20 and 22. Conversely GSA 6, 9, and 17 showed very low ecosystem sustainability of the fisheries, with the Northen Central Adriatic Sea (GSA 17) the lowest 14.3% (±9.1). These figures are coherent with the high fishing pressure on these systems (number of trawlers per unit surface of shelf). Ecosystems in GSA 6, 9, and 17 appear thus overexploited with considerable losses in secondary productions and represent areas where exploitation is ecologically inefficient and also characterized by economically low efficient fisheries.

Unfortunately not all GSAs have exemplificative ecosystem model to analyse, and clearly the ones available suffer for representing different periods in the last decades, might embeds different biological resolution and processes, and might have different degree of accuracy according to data availability. Nevertheless, the picture is coherent with fishing capacity, effort and catches for the overlapping GSAs. Results point to general good conditions for areas dominated historically by artisanal and small scale fisheries such as the Greek Ionian Sea, GSA 20, (Moutopoulos et al., 2013) or where fisheries is developed but still working within profitable conditions such as the Tunisian GSAs (Hattab et al., 2013). Areas such as the western GSA17, with long history of fisheries exploitation (Fortibuoni et al., 2010), with very impacting gears active (such as the rapido trawling; Pranovi et al., 2000), with several ecosystem impacts documented (e.g., Giani et al., 2012) and with several stocks assessed as overfished (**Table 2**), resulted to be in a condition that can be summarized as a low profitable bio-economic equilibrium.

CONCLUSIONS

It is straightforward that the current level of fishing pressure in the Mediterranean basin, exerted by a large variety of fishing vessels and fishing gears, has impaired the productivity of commercial stocks, increased the extinction risks for sensible species, such as elasmobranchs, and contributed to disrupt the productivity and functions of the ecosystem.

We showed that single species and ecosystem models return a coherent pattern where ecosystem overfishing is combined with a high proportion of commercial stocks out of safe biological limits. This is in turn the result of a prolonged high fishing pressure where the effect of diffuse artisanal fleets is exacerbated by high pressure from vessels using towed gears (e.g., bottom and pelagic trawlers, beam trawlers). The fishing effort has increased in an uncontrolled way for decades in many Mediterranean areas (Garcia, 2011), and although measures to freeze the effort and reduce the capacity of the fleet are ongoing in EU Mediterranean countries also thanks to EU regulations, there are not yet clear signs of an inversion of the trend. As a matter of fact, Cardinale and Scarcella (2017), clearly shown that one of the major reasons for the alarming situation of Mediterranean Sea stocks can be found in the ineffectiveness of the putative effort reductions to control fishing mortalities, the continuous non-adherence to the scientific advice, and the existence of ineffective national management plans as a primary management measure.

It is widely recognized that managing multi-species, multi-fleets fisheries is a complex task where the achievement of single species targets (i.e., MSY) for a multiple stocks can be challenging due to species interactions (e.g., prey-predator relationships, competition, etc.) but also due to indirect interactions of mixed fisheries (Walters et al., 2005; Mackinson et al., 2009), especially in a fast changing ecosystem such as the Mediterranean. The rapid warming, combined with the expansion of non-indigenous species is definitely changing the suitability of the habitats for traditional commercial species with effects on their resilience to fishing (Libralato et al., 2015). The recent collapse of small pelagic fishery in the Gulf of Lions is a clear example where poor fish growth, size and body condition and ultimately biomass seem to be due to bottom-up control characterized by changes in food availability and increasing potential trophic competition (Brosset et al., 2016). Exaggerated fishing pressure represents a threat for populations making them more fragile and less resilient to other pressures and changes, and ultimately increasing the risk of collapse for the fisheries themselves.

In this context, the development of a more effective management regime for Mediterranen fisheries is extremely urgent to prevent that unregulated fishing and climate forcing might disrupt the secondary productivity of the ecosystem with major impacts on the goods and services provided.

The poor management is likely the result of the intrinsic complexity of managing human activities in the Mediterranean basin, where nations with major differences in the governance systems, socio-economic priorities and development objectives, share common natural resources (Micheli et al., 2013). However, a different result in terms of governance and sustainability was expected for fisheries in EU Mediterranean countries considering the policy objectives identified by regulations such as the Common Fisheries Policy (CFP), and the EU reg. 1967 since 2006.

Only recently were set the first attempts to develop management strategies at the international scale by GFCM with the support of the EU, as for example for deep water rose shrimp and hake fisheries in the Strait of Sicily. The ongoing process in Mediterranean European waters appears however too slow to achieve the MSY for the main commercial stocks by 2020.

The Mediterranean EU regulation 1967/2006 and the CFP have mostly failed in their mandate to achieve sustainability for fisheries in EU Mediterranean waters, thus not providing long-term sustainability and profitability to the fishing enterprises (STECF, 2015). This is in contrast to what observed in recent years in NE Atlantic, where the actions already implemented under the CFP have led to an improvement in the status of many commercially important fish stocks toward levels that are capable of producing MSY (Cardinale et al., 2013). Although the high-level seminar on the state of stocks in the Mediterranean and on the CFP approach held in February 2016 (http://ec.europa.eu/fisheries/high-level-seminar-state-stocks-mediterranean-and-cfp-approach_en) has stressed the need of urgent actions to inverse the ongoing negative trend, any major management action to quickly reverse the trend has been put in place so far.

Similar problems are being experienced throughout the world and for sure, several policy-oriented instruments have been enacted at the international level in recent years, which call upon relevant management bodies and Regional Fisheries Management Organizations (RFMOs) to be actively involved in the protection of marine biodiversity and sustainable use of fishery resources. In particular, the new CFP along with the most recently, UN SDG 14, FAO SO2, and the Aichi Targets all stress the importance of reducing overfishing and securing healthy ecosystems for the benefit of present and future generations.

AUTHOR CONTRIBUTIONS

FC: contribution to the design of the study, catch-effort review and analysis, and discussion of results; GS: contribution to the design of the study, stock assessments review, and discussion of results; SL: contribution to the design of the study, ecosystem models review and analysis, and discussion of results.

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Mediterranean Sea: A Failure of the European Fisheries Management System

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North East Atlantic and the Mediterranean Sea fisheries are governed by the European Common Fisheries Policy (CFP). Despite the fact that both areas are managed under the same broad fishery management system, a large discrepancy in management performance occurs, with recent considerable improvement of stock status witnessed in the North East Atlantic and a rapidly deteriorating situation in the Mediterranean Sea. The control of fishing effort combined with specific technical measures, such as gear regulation, establishment of a minimum conservation reference size, and selective closure of areas and seasons, is the main management strategy adopted by Mediterranean Sea EU countries. On the other hand TAC (Total Allowable Catches) is the major regulatory mechanisms in the North East Atlantic. Here, we analyzed all available stock assessment and effort data for the most important commercial species and fleets in the Mediterranean Sea since 2003. The analysis shows that there is no apparent relationship between nominal effort and fishing mortality for all species. Fishing mortality has remained stable during the last decade, for most species, with a significant decline observed only for red mullet and giant red shrimp but an increase for sardine stocks. Also, current F is larger or much larger than F_{MSY} for all species. Despite catch advice are produced by STECF each year, the realized catches have usually been much larger than the scientific advice. A recent analysis argued that this dichotomy might be due to several factors, such as the better enforcement of monitoring control and surveillance in North East Atlantic, the more complex socio-economic situation and the less effective management governance in the Mediterranean Sea. Here we argue instead that major reasons for the alarming situation of Mediterranean Sea stocks can be found in the ineffectiveness of the current effort system to control F, the continuous non-adherence to the scientific advice and inadequacies of existing national management plans as a key management measure. It is therefore undoubted that alternatives management measures as a TAC based system are necessary if Europe is willing to achieve the objectives of the CFP before 2020 in the Mediterranean Sea.

Keywords: Mediterranean, common fishery policy, management, effort, failure

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INTRODUCTION

In 2002, the World Summit on Sustainable Development (WSSD; United nations, 2002) established the deadline for the recovery of world's depleted fish stocks to biomass levels that can produce the maximum sustainable yield (B_{MSY}) no later than 2015. The Common Fisheries Policy (CFP) fixes the rules and directions for a sustainable exploitation of marine resources exploited by European fishing fleets (Regulation (EU) No 1380/2013; EU, 2013). The main objective contained in Article 2(2) of the new CFP is the restoration and/or maintenance of populations of harvested species above B_{MSY} levels. This approach would ensure that fisheries are sustainable and profitable in the long term, and that comply with European Union (EU) environmental legislation, as well as with international law principles. All future fisheries measures, and all actions undertaken by EU and Member State institutions, must serve to deliver these objectives, complying with the requirement to set fishing levels below F_{MSY} [i.e., fishing mortality (F) that delivers B_{MSY}] and aimed at achieving stock levels above B_{MSY}. Any measures that take a different approach will be in breach of the CFP, i.e., unlawful.

The first time that the CFP has been enforced was in the 1970s and has been successively updated in 2002 and recently in 2014. The CFP keystone is the sustainable exploitation of marine resources both in environmental and socio-economic terms directing toward a dynamic fishing industry and ensuring a fair standard of living for fishing communities. The current CFP specifies that between 2015 and 2020 exploitation is carried out according MSY principles and is able to maintain fish stocks in the long term. In the case of the impact of fishing on the marine environment is not fully comprehended, the CFP adopts a precautionary approach and seeks for more selective fisheries with a complete ban of discards. Similarly, also the Marine Strategy Framework Directive (MSFD; EU-COM, 2008, 2010) requires EU Member States to take measures to achieve Good Environmental Status (GES) of all European marine waters by 2020.

After 8 years from the adoption of WSSD and the enforcement of MSFD with the definition of GES and targets in each Member State (MS), and the concurrent application of the CFP, Europe has made great progress toward MSY for stocks inhabiting the North East Atlantic (e.g., Cardinale, 2011; Cardinale et al., 2012; Fernandes and Cook, 2013) but it is still far from achieving its objectives for the Mediterranean Sea marine resources (e.g., Colloca et al., 2013; Vasilakopoulos et al., 2014). Notwithstanding the enforcement of the EU Data Collection Regulation (EU, 2000) in the early 2000s by all EU MSs, and the rapid increase in the number of assessed stocks by the General Fisheries Commission for the Mediterranean (GFCM) and the European Scientific, Technical and Economic Committee for Fisheries (STECF), Mediterranean Sea marine resources are still exploited above the levels that deliver the maximum sustainable yield and no signs of recovery are evident (Vasilakopoulos et al., 2014). Particularly, in the Mediterranean Sea, the achievements of WSSD targets is at risk to be further delayed by the management systems currently enforced at the national and EU level.

From the management perspective, Mediterranean Sea countries are limited mainly to control fishing effort and fishing capacity together with specific technical measures, such as gear regulation (mainly mesh size and net configuration, in particular for purse seine), establishment of a minimum conservation reference size, and closures of areas and seasons for fishing. Moreover, the Article 19 of Council Regulation (EU, 2006; hereafter referred to as "the Mediterranean Regulation") foreseen that management plans within their territorial waters are adopted for trawling and other fishing activities. In this context, it is important to notice that spatial and temporal closures apply mainly to trawls, which are prohibited within 3 nautical miles from the coast or within the 50 m isobath, where this is closer to the coast. Also, temporal closures regard bottom and mid-water trawl nets are mainly enforced for 30–45 days during summer (Demestre et al., 2008). A second set of management measures in the Mediterranean Sea incorporate the establishment of permanent marine protected areas. However, the extension of MPA is still rather limited in the Mediterranean Sea, covering around 9.5% of the EU water within 200 nm and being mostly located in the Western Mediterranean (http://www.eea.europa.eu/data-and-maps/figures/regional-seas-surrounding-europe-and-2).

Conservation reference points are established in national management plans in order to recover or maintain the stock within safe biological limits ensuring the sustainable exploitation of stocks and that impact of fishing activities on marine ecosystems is kept at sustainable levels. An important feature of these plans is that they should be solely adopted within the territorial waters of each MS, and thus do not consider the transboundary dimension of most of the stocks exploited in the Mediterranean Sea.

Here, we collated and analyzed all available information on Mediterranean Sea stocks. We analyzed the current stock status of Mediterranean Sea marine resources and compared it to the F_{MSY} target. We also explored the temporal trends in F to determine if the status of stock is improving or worsening. Further, we analyzed the relationship between F and nominal fishing effort for stocks fished by EU MSs only.

MATERIALS AND METHODS

We collated information on the Mediterranean fish stocks from relevant reports of STECF (https://stecf.jrc.ec.europa.eu/reports/medbs) and GFCM SAC (http://www.fao.org/gfcm/reports/statutory-meetings/en/), published over the period 2007–2015. These reports were used to extract estimates of fishing mortality (F), fishing mortality which corresponds to MSY (F_{MSY}), SSB (Stock spawning biomass), recruitment, catches, and advised catches for each stock. Collated data were stored in a database which contains all available information on the status of 142 stocks (as combination of species and GSAs (i.e., Geographical Sub-Areas) derived from assessments conducted between 2007 and 2014 (**Table 1**, **Figure 1**). In total, more than 500 stock assessments results were collated, which cover 26 different species and 27 GSAs or combination of GSAs. However, not all stocks

TABLE 1 | List of species and stocks (by GSA or combination of GSAs) collated in this study with the associated reference where the stock assessment has been conducted.

Scientific name	GSAs	References
Merluccius merluccius	1	GFCM, 2011a
		GFCM, 2012a
		GFCM, 2014a
		GFCM, 2015a
		STECF, 2008b
		STECF, 2008c
		STECF, 2011a
		STECF, 2011b
		STECF, 2013a
		STECF, 2015b
	5	GFCM, 2007a
		GFCM, 2008a
		GFCM, 2009a
		GFCM, 2010a
		GFCM, 2011a
		GFCM, 2012a
		GFCM, 2014a
		GFCM, 2014c
		GFCM, 2015a
		STECF, 2008b
		STECF, 2008c
		STECF, 2010a
		STECF, 2012a
		STECF, 2015b
	6	GFCM, 2007a
		GFCM, 2008a
		GFCM, 2009a
		GFCM, 2010a
		GFCM, 2012a
		GFCM, 2014c
		STECF, 2008a
		STECF, 2008b
		STECF, 2008c
		STECF, 2009a
		STECF, 2010a
		STECF, 2011b
		STECF, 2014a
		STECF, 2015b
	7	GFCM, 2008a
		GFCM, 2009a
		GFCM, 2010a
		GFCM, 2011a
		GFCM, 2012a
		GFCM, 2014a
		GFCM, 2015a
		STECF, 2008a
		STECF, 2008b
		STECF, 2008c
		STECF, 2010a
		STECF, 2012a
		STECF, 2012b
		STECF, 2013a
		STECF, 2014a
		STECF, 2015b
	8	STECF, 2008b
	9	GFCM, 2007a
		GFCM, 2011a
		GFCM, 2015a
		STECF, 2008a
		STECF, 2008b
		STECF, 2008c
		STECF, 2009a
		STECF, 2010a
		STECF, 2011b
		STECF, 2014a
		STECF, 2015b
	10	GFCM, 2009a
		GFCM, 2014c
		STECF, 2008a
		STECF, 2008b
		STECF, 2009a
		STECF, 2010a
		STECF, 2012a
		STECF, 2013a
		STECF, 2015b
	11	STECF, 2008b
		STECF, 2008c
		STECF, 2009a
Merluccius merluccius	11	STECF, 2010a
		STECF, 2012a
		STECF, 2012b
		STECF, 2012d
		STECF, 2015b
	16	STECF, 2008a
	17	GFCM, 2014c
		STECF, 2008b
		STECF, 2008c
		STECF, 2010a
		STECF, 2012d
	18	GFCM, 2010a
		GFCM, 2011a
		GFCM, 2012a
		GFCM, 2014a
		GFCM, 2014c
		GFCM, 2015a
		STECF, 2008b
		STECF, 2012a
		STECF, 2013a
	19	GFCM, 2015a

(Continued)

TABLE 1 | Continued

Scientific name	GSAs	References
		STECF, 2008b
		STECF, 2012d
		STECF, 2013a
		STECF, 2016
	20	STECF, 2008b
		STECF, 2012c
	22	STECF, 2008a
	12-16	GFCM, 2014a
		GFCM, 2014c
		GFCM, 2015a
	15-16	STECF, 2008b
		STECF, 2008c
		STECF, 2010a
	1-5-6-7	STECF, 2015b
	17-18	STECF, 2016
	22-23	STECF, 2008b
		STECF, 2012c
	9-10-11	STECF, 2015b
Mullus barbatus	1	GFCM, 2008a
		STECF, 2008b
		STECF, 2011a
		STECF, 2011b
		STECF, 2015a
	5	GFCM, 2008a
		GFCM, 2010a
		GFCM, 2014a
		STECF, 2008b
		STECF, 2010a
		STECF, 2012a
		STECF, 2013a
	6	GFCM, 2008a
		GFCM, 2010a
		GFCM, 2011a
		GFCM, 2014a
		STECF, 2008b
		STECF, 2008c
		STECF, 2010a
		STECF, 2013a
		STECF, 2014a
	7	GFCM, 2009a
		GFCM, 2010a
		GFCM, 2011a
		GFCM, 2012a
		GFCM, 2014a
		GFCM, 2014c
		GFCM, 2015a
		STECF, 2008b
		STECF, 2010a
		STECF, 2012a
		STECF, 2012b

(Continued)

TABLE 1 | Continued

Scientific name	GSAs	References
		STECF, 2014a
	8	STECF, 2008b
	9	GFCM, 2010a
		GFCM, 2011a
		STECF, 2008b
		STECF, 2008c
		STECF, 2009a
Mullus barbatus	9	STECF, 2010a
		STECF, 2011b
		STECF, 2012d
		STECF, 2014a
	10	GFCM, 2014a
		GFCM, 2014c
		STECF, 2008b
		STECF, 2008c
		STECF, 2010a
		STECF, 2012a
	11	STECF, 2008b
		STECF, 2010a
		STECF, 2012a
		STECF, 2012d
		STECF, 2013a
	15	GFCM, 2009a
	16	STECF, 2008b
	17	GFCM, 2014a
		GFCM, 2015a
		STECF, 2008b
		STECF, 2008c
		STECF, 2012b
		STECF, 2013a
	18	GFCM, 2015a
		STECF, 2008b
		STECF, 2012b
		STECF, 2015a
	19	GFCM, 2014a
		STECF, 2008b
		STECF, 2012d
		STECF, 2016
	20	STECF, 2008b
		STECF, 2012c
	25	GFCM, 2009a
		GFCM, 2011a
		GFCM, 2015a
		STECF, 2008b
		STECF, 2008c
		STECF, 2009a
		STECF, 2010a
	1-3	GFCM, 2015a
	15-16	GFCM, 2011a
		GFCM, 2012a

(Continued)

TABLE 1 | Continued

Scientific name	GSAs	References
		STECF, 2011b
		STECF, 2012b
	17-18	STECF, 2016
	22-23	STECF, 2008b
		STECF, 2012c
Boops boops	20	STECF, 2012c
	25	GFCM, 2011a
		GFCM, 2015a
	22-23	STECF, 2012c
Galeus melastomus	9	GFCM, 2011c
		STECF, 2011a
		STECF, 2011b
Lophius budegassa	1	STECF, 2015a
	5	STECF, 2012d
		STECF, 2015a
	6	STECF, 2012b
		STECF, 2015a
	7	STECF, 2012b
	15-16	GFCM, 2011a
		STECF, 2012b
Micromesistius poutassou	1	STECF, 2012d
	6	STECF, 2012b
		STECF, 2014a
	9	STECF, 2012b
		STECF, 2014a
Mullus surmuletus	5	GFCM, 2007a
		GFCM, 2008a
		GFCM, 2009a
		GFCM, 2010a
		GFCM, 2011a
		GFCM, 2012a
		GFCM, 2014a
		GFCM, 2014c
		GFCM, 2015a
		STECF, 2010a
		STECF, 2013a
	9	GFCM, 2011a
		STECF, 2011a
		STECF, 2011b
	11	STECF, 2013a
	15	GFCM, 2009a
	20	STECF, 2012c
	25	GFCM, 2011a
	15-16	GFCM, 2014a
		STECF, 2013a
	22-23	STECF, 2012c
Pagellus bogaraveo	1-3	GFCM, 2008a

(Continued)

TABLE 1 | Continued

Scientific name	GSAs	References
		GFCM, 2012a
Pagellus erythrinus	9	STECF, 2010a
		STECF, 2011b
	15-16	GFCM, 2011a
		GFCM, 2012a
		STECF, 2011b
		STECF, 2012b
Phycis blennoides	9	STECF, 2012d
Raja asterias	9	GFCM, 2011c
Raja clavata	9	GFCM, 2011c
	15-16	GFCM, 2011c
Scyliorhinus canicula	9	GFCM, 2011c
Solea solea	9	STECF, 2011a
	17	GFCM, 2007a
		GFCM, 2008a
		GFCM, 2010a
		GFCM, 2011a
		GFCM, 2012a
		GFCM, 2014a
		GFCM, 2015a
		STECF, 2009a
		STECF, 2010a
		STECF, 2011b
		STECF, 2012d
		STECF, 2013a
		STECF, 2016
Spiacara flexuosa	20	STECF, 2012c
	22-23	STECF, 2012c
Spiacara smaris	20	STECF, 2012c
	22-23	STECF, 2012c
	25	GFCM, 2014a
		STECF, 2011b
Trisopterus minutus	9	STECF, 2012b
Engraulis encrasicolus	1	GFCM, 2007b
		GFCM, 2008b
		GFCM, 2009b
		GFCM, 2010b
		STECF, 2008c
		STECF, 2010a
	6	GFCM, 2007b
		GFCM, 2008b
		GFCM, 2009b
		GFCM, 2010b

(Continued)

TABLE 1 | Continued

Scientific name	GSAs	References
		GFCM, 2011b
		GFCM, 2014b
		GFCM, 2014d
		STECF, 2008a
		STECF, 2008c
		STECF, 2010a
	7	GFCM, 2007b
		GFCM, 2008b
		GFCM, 2009b
		GFCM, 2010b
		GFCM, 2011b
		GFCM, 2012b
		GFCM, 2014b
		GFCM, 2014d
		GFCM, 2015b
		STECF, 2008c
	9	STECF, 2010a
		STECF, 2011b
	16	GFCM, 2008b
		GFCM, 2009b
		GFCM, 2010b
		GFCM, 2011b
		GFCM, 2012b
		GFCM, 2014b
		STECF, 2009a
		STECF, 2010a
		STECF, 2012d
	17	GFCM, 2007b
		GFCM, 2008b
		GFCM, 2009b
		GFCM, 2010b
		GFCM, 2011b
		GFCM, 2012b
		GFCM, 2014b
		STECF, 2008c
		STECF, 2009a
		STECF, 2012d
		STECF, 2013b
	18	GFCM, 2007b
	19	STECF, 2013a
	20	STECF, 2010a
	22	GFCM, 2009b
		STECF, 2008c
		STECF, 2009a
		STECF, 2010a
		STECF, 2012a
		STECF, 2013a
	17-18	GFCM, 2014d
		GFCM, 2015b
		STECF, 2014a
Sardina pilchardus	1	GFCM, 2007b
		GFCM, 2008b
		GFCM, 2010b
		GFCM, 2014b
		STECF, 2008c
		STECF, 2010a
		STECF, 2013a
	3	GFCM, 2014d
		GFCM, 2015b
	6	GFCM, 2007b
		GFCM, 2008b
		GFCM, 2010b
		GFCM, 2011b
		GFCM, 2014b
		GFCM, 2014d
		STECF, 2008a
		STECF, 2008c
		STECF, 2010a
		STECF, 2015a
	7	GFCM, 2007b
		GFCM, 2008b
		GFCM, 2011b
		GFCM, 2012b
		GFCM, 2014b
		GFCM, 2014d
		GFCM, 2015b
		STECF, 2013a
	9	STECF, 2012b
		STECF, 2013a
		STECF, 2015a
	16	GFCM, 2008b
		GFCM, 2010b
		GFCM, 2011b
		GFCM, 2012b
		GFCM, 2014b
		GFCM, 2015b
		STECF, 2009a
		STECF, 2010a
		STECF, 2012d
	17	GFCM, 2007b
		GFCM, 2008b
		GFCM, 2010b
		GFCM, 2011b
		GFCM, 2012b
		GFCM, 2014b
		STECF, 2008c
		STECF, 2009a
		STECF, 2012a
		STECF, 2012d
		STECF, 2013a
	18	GFCM, 2007b
		STECF, 2013a

(Continued)

TABLE 1 | Continued

Scientific name	GSAs	References
	20	STECF, 2010a
	22	STECF, 2008c
		STECF, 2009a
		STECF, 2010a
		STECF, 2012a
	1-3	GFCM, 2012b
	17-18	GFCM, 2014d
		GFCM, 2015b
		STECF, 2014a

resulted in an analytical stock assessment. Also, data on fishing effort by fisheries in terms of Kw/Days at Sea (i.e., nominal effort) and Gross tonnage/Days at sea were extracted and collated for each GSA and fisheries. This represents the most complete database of stock assessment results for the Mediterranean region available to date.

For the exploration of temporal trends in F and effort, we selected the main species and fisheries operating in the Mediterranean Sea. The species selected were European hake, red mullet, deep-water rose shrimp, Norway lobster, giant red shrimp, blue and red shrimp, European anchovy, and sardine. The landings of these species in 2014 constituted approximately 55% of the total landings in the European GSAs of Mediterranean Sea and they are considered as the target species in all GSAs (2015-Economic Data Call; **Table 2**). The fisheries selected were demersal trawl operating on the shelf (hereafter defined as demersal coastal trawl), demersal trawl operating in the deep (hereafter defined as demersal deep trawl), purse seine, pelagic trawls and net, lines, and traps combined (hereafter defined as passive gears) (**Table 3**). The gears included in each of the fisheries selected are summarized in **Table 3**. Here, we used both nominal effort in Kw/Days at sea and Gross Tonnage/Days at sea as a measure of effort in the analysis.

Statistical Analysis

Generalized Additive Models (GAMs; Hastie and Tibshirani, 1990) were used to account for the unbalanced design in the data available between years and GSAs. The model non-linearity, a common characteristic of biological data, is one of the main benefits that GAMs can handle. Fishing mortality was scaled by the level of F_{MSY} in order to make the different stocks comparable in the analysis. A normal distribution (Minami et al., 2007) to model the ration F/F_{MSY} has been used.

For each species a GAM model was fitted:

$$F/F_{MSY} \sim s(\text{year}) + s(\text{effort}) + (\text{GSA})$$

For hake, demersal coastal trawl, mixed trawl and net, and lines effort were included. For red mullet, only demersal coastal trawl effort was considered. For deepwater pink shrimp and Norway lobster, mixed and deep demersal trawl effort was used while for anchovy and sardine, purse seines and pelagic trawlers effort was used (**Table 3**). The combination among species and gear/fisheries have been made in accordance with the last STECF available assessments (STECF, 2015a,b, 2016).

The isotropic smooth (i.e., thin plate regression spline) function (Wood, 2004) has been used to model Year and effort while GSA was modeled as a factor. The maximum number of knots was limited for the smooth term of effort ($k \leq 3$) and year ($k \leq 7$), in order to simplify the output interpretation. For each species model, two different link functions were tested, a log link which assumes constant variance and a identify link which assumes constant coefficient of variation and hence a variance proportional to the square of the mean. The best model was chosen using the AIC (Akaike Information Criteria) (Akaike, 1974). Effort data was available only from 2002 and thus only these years (i.e., 2002–2014) were included in the analysis.

The assumptions of variance homoscedasticity and normal distribution of data have been explored throughout the analysis of the residuals. Similarly, the residuals were employed to inspect analyses the departure from the model assumptions or other anomalies in the data or in the model fit using graphical methods (Cleveland, 1993).

Comparison between Forecast Catches and Real Catches

In most of the stock assessment carried out in the framework of GFCM and STECF short-term forecasts have been conducted for 2 or 3 years after the reference year of the assessment. The short-term predictions were usually implemented in R (https://www.r-project.org/) using the FLR libraries and based in most of the cases on the results of the Extended Survivor Analyses (XSA, Darby and Flatman, 1994) or other assessment models. Several scenarios of F were tested as well as the F which is in accordance with the F_{MSY}. The method employed allowed to estimate the catches relative to the F reference points assuming a constant recruitment in the following 2 years equal to the geometric mean of the previous 3 years. Such reference catches have been then compared with the real catches for each stock analyzed.

RESULTS

There is no difference in the model results when using Kw/Days at sea or Gross Tonnage/Days at sea and thus only results for Kw/Days at sea were presented here. This was expected as Kw/Days at sea and Gross Tonnage/Days at sea are highly significantly correlated for all GSA and fisheries selected here ($r^2 = 0.91$; $p < 0.05$).

Table 4 summarize the detailed results for all GAMs fitted. A total of eight GAMs were fitted. The significant effects for all models fitted are presented in **Figure 2**. Model assumptions of normality and homogeneity of variance have been respected, as showed by the analysis of the residuals (data not shown).

Generally all GAMs explained a rather large part of the deviance (76.3–95.1%) with an r^2 which ranged between 0.70 and 0.93. The log link was selected as the best model based on the AIC for hake, red mullet, Norway lobster, and sardine. The identity

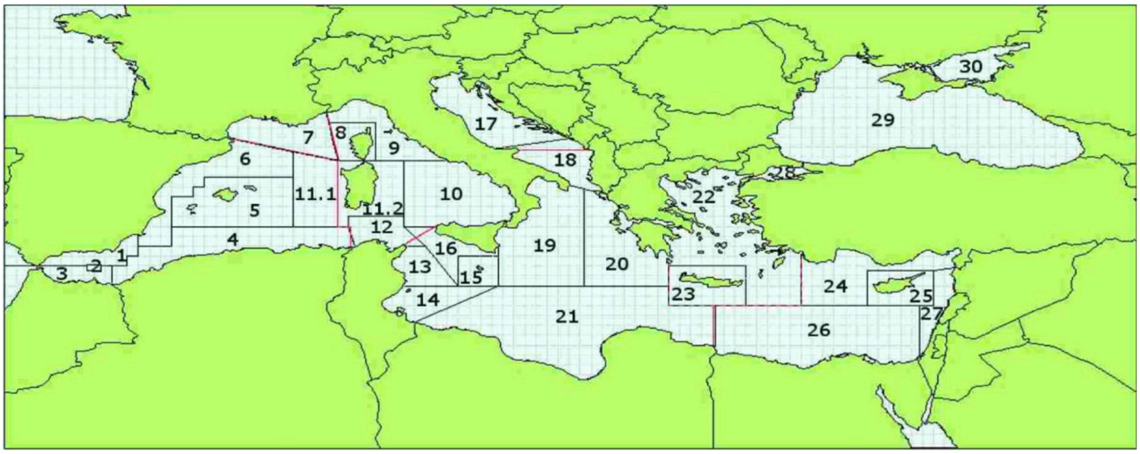

FIGURE 1 | Map of the GFCM Geographical Sub-Areas (GSAs) established in the resolution GFCM/33/2009/2 (GFCM, 2009d).

link resulted in the best model for deep water pink shrimp, giant red shrimp, blue and red shrimp, and sardine (**Table 4**).

Concerning the effect of the different predictors included in the models, the results of the GAM analysis showed that effort was not significantly related to F/F_{MSY} in any of the model fitted except for deep water pink shrimp (**Figure 2**). However, the shape of the effect of effort on F/F_{MSY} for deep water pink shrimp is contradictory to the expectations (i.e., decreasing F/F_{MSY} with increasing effort) and thus it was considered to be spurious. On the other hand, the effect of GSA was significant for all models. The year effect was significant only for red mullet, giant red shrimp (decreasing trend in F/F_{MSY} over time) and sardine (increasing trend of F/F_{MSY} over time).

The average ratio F/F_{MSY} is larger than 1 for all species, ranging from 1.7 to 8.1 (Giant red shrimp and hake, respectively; **Table 4**). Even for red mullet and giant red shrimp, for which the ratio F/F_{MSY} has significantly declined over time, the value of the last year (i.e., 2014) is still above 1 (2.5 and 1.1, for red mullet and giant red shrimp, respectively).

In **Table 5** are reported the comparisons between the forecasted yearly catches in accordance with F_{MSY} and the realized catches estimated for the target stocks previously analyzed. In almost all cases realized catches have been much larger than the forecasted ones, with an average catch over the analyzed time period (i.e., 2010–2014) being around 178% larger than the scientific advice.

DISCUSSION

In recent years European fisheries managers have witnessed the success of the European CFP in the north (i.e., North East Atlantic, Cardinale et al., 2012; Fernandes and Cook, 2013) and at the same time, its failure in the south (i.e., Mediterranean Sea, Colloca et al., 2013; Vasilakopoulos et al., 2014). Thus, despite the fact that both areas are managed under the same broad fishery policy (i.e., European CFP), a large discrepancy in management performance still occur between the North East Atlantic and the Mediterranean Sea.

The fishing mortality exerted on the North East Atlantic has shown a rapid and general decline during the last 15 years and even the spawning stock biomass has started to show clear signs of increasing for several stocks in the North East Atlantic area (www.ices.dk). On the other hand, Mediterranean stocks have largely declined in the last 15 years and their exploitation level has raised or remained above the F_{MSY} level during the same period of time (Vasilakopoulos et al., 2014; this paper). Here we showed that up to 2014, the average exploitation rate for the main demersal and small pelagic stocks of the Mediterranean Sea is around three times the estimated level of F_{MSY}, with a general similar pattern across species and area, which confirms analyses recently conducted (STECF, 2015c). Moreover, as we have mostly only a snapshot of the last decade for Mediterranean stocks (i.e., generally from the beginning of the 2000s to today), and, as F has been estimated to be very high since the beginning of the time series (Colloca et al., 2013; Vasilakopoulos et al., 2014), the decline in stock biomass might have started much before and being more pronounced than described by current assessment models. This has been demonstrated by those assessments with a longer time series, as small pelagics in the Adriatic Sea (time series: 1975–2014; GFCM, 2015b) and common sole in the Northern Adriatic Sea (time series: 1970–2014; GFCM, 2015a; STECF, 2016).

The CFP obviously applies to the Mediterranean Sea as well, although it has been argued that, as several Mediterranean stocks are shared with non EU countries on the southern part of the basin, the unsuccessful management of the CFP could be attributed to the fact that Europe has no jurisdiction on these stocks. However, there are several Mediterranean stocks that are solely distributed within EU territorial waters (i.e., several Spanish, France and Italian stocks located in GSAs 4–11) and for which therefore the CFP is the primary (and only) management instrument for assuring their long term sustainable exploitation. Here we showed that the average

TABLE 2 | Landings by species, GSA and gear in 2014 for species included in the GAM models (source: 2015 Economic data call).

Species	Fishery	GSA 1	GSA 5	GSA 6	GSA 7	GSA 8	GSA 9	GSA 10	GSA 11	GSA 15	GSA 16	GSA 17	GSA 18	GSA 19	GSA 20	GSA 22	GSA 23	GSA 25	Total
European anchovy	Demersal coastal trawl	0.3		106.1	1547.6	1.6	41.2	269.7			78.2	218.1	36.7	0.1	0.0	418.7			2718.0
	Passive gears	4.6		4.6	683.7	0.2	19.4	62.5				8.5		17.7		26.7		1.0	829.0
	Pelagic trawl										677.2	17012.8	2529.9						20211.0
	Purse seine	4467.2	277.3	14735.4	133.0		3390.8	3029.1			1349.6	11345.1	800.1	103.5	403.1	6556.1	1.3		46592.0
Sardine	Demersal coastal trawl	0.8		27.2	76.6	1.3	11.6	37.8			43.8	1646.8	11.6	21.6	6.0	70.9	1.7	0.2	1958.0
	Passive gears	88.8		8.9	75.2	0.7	10.8	78.9				28.8		29.6		758.8	0.0	0.3	1081.0
	Pelagic trawl										341.4	17011.2	1751.2						19104.0
	Purse seine	7444.3	138.3	7915.5	686.4		1782.4	729.6			1085.2	57438.5	605.4	83.6	520.1	4720.0	0.3		83150.0
Blue and red shrimp	Demersal deep trawl	198.3	112.0	419.0	34.8		83.6	7.3	89.8	1.3	116.6		2.7	299.5					1365.0
	Passive gears		0.0	0.2				1.4											1.6
Giant red shrimp	Demersal deep trawl	0.2	3.9	4.3	0.1		16.8	436.8	123.9	25.1	1310.2	3.9	8.1	320.0	25.5	0.6			2280.0
	Passive gears							17.2											17.0
Deep-water rose shrimp	Demersal coastal trawl	34.6	2.2	18.0	4.0	1.5	561.4	497.3	30.2	21.2	5310.4	572.3	615.5	421.5	20.3	2284.3	37.1		10432.0
	Passive gears		0.0	0.0	0.5	0.0	0.0	11.8		0.8		0.2	22.3	1.8	1.7	13.8			53.0
Norway lobster	Demersal coastal trawl	21.9	21.7	296.6	26.7	18.1	111.5	16.6	35.3	1.7	249.0	867.1	444.7	84.8	3.0	256.7	0.1	0.1	2455.0
	Passive gears	0.1	0.0	0.1	0.5	0.0	0.1	4.8	0.0			19.1	0.0		3.9	112.2			140.0
European hake	Demersal coastal trawl	124.6	90.2	1501.4	1529.2	5.8	1010.5	345.4	134.5	16.1	1376.0	2630.0	1560.0	209.9	300.4	1484.0	53.6	0.6	12372.0
	Passive gears	36.2	0.1	232.8	138.9	0.4	263.6	925.8	124.1	5.0	91.6	128.7	303.6	530.1	284.2	557.4	3.2	2.2	3627.0
Red mullet	Demersal coastal trawl	49.7	14.7	498.7	22.7		1098.3	342.0	258.6	12.1	417.4	3576.0	1218.8	102.7	118.3	746.4	107.1	15.7	8599.0
	Passive gears	10.8	0.3	62.2			83.2	95.9	5.4	0.2	2.6	38.8	53.4	148.4	185.6	816.9	26.0	8.8	1538.0
Total landings of species analyzed by GSA		12482.1	660.7	25831.0	4960.0	29.6	8485.3	6910.0	801.9	84.0	12449.0	112546.0	9964.0	2374.0	1872.0	18823.0	230.4	28.8	21852
Total landings by GSA		29467.1	2698.0	43775.8	14338.4	375.1	17419.5	18524.2	5981.5	2379.9	19,850.6	164808.1	19917.6	10104.1	6005.5	40642.8	1059.9	1218.9	398567
Percentage by GSA		42.4	24.5	59.0	34.6	7.9	48.7	37.3	13.4	3.5	62.7	68.3	50.0	23.5	31.2	46.3	21.7	2.4	54.8

exploitation rate for the main demersal and small pelagic stocks of the Mediterranean Sea exploited solely or mostly by European fleets is around three times the estimated level of F_{MSY}, with a general similar pattern across species and areas. This pattern has been observed for more than a decade and there are no signs of a decline in the exploitation in the latest years.

A striking difference in the management of marine fish stocks between North East Atlantic and the Mediterranean Sea is that Mediterranean Sea is primarily managed by effort control while North East Atlantic stocks management has been based primarily on TACs, which are regularly provided by ICES to the EC. Recent trends in decision making indicate that scientific advice in the North East Atlantic has been more closely followed in later years, with the proportion of EU TACs set above scientific advice that has declined from 33% in 2001 to only 7% in 2015 (Carpenter et al., 2016) while no such trend exists for Mediterranean stocks. In fact, notwithstanding that the scientific advice (i.e., TAC advice) has been provided by STECF since 2008, it has rarely been followed or implemented, with realized catches being much larger than the scientific advice (178%; this paper). Even the realized reductions in effort (e.g., a minimum reduction of bottom-trawling fishing effort in the Mediterranean is foreseen by GFCM resolution RES-GFCM/33/2009/1, GFCM, 2009c) have always been much smaller than what deemed necessary by the scientific advice (Colloca et al., 2013). Moreover, another key difference between North East Atlantic and Mediterranean is the low level of compliance and enforcement in the Mediterranean compared to the North East Atlantic (Vasilakopoulos et al., 2014). This is an important element of any fisheries management system, which has surely contributed to the current situation of Mediterranean Sea stocks.

TABLE 3 | Combination of species assigned to each gear and fisheries analyzed in the present study.

Fisheries	Gears	Species associated
Demersal coastal trawl	Bottom otter trawl Beam trawl	Norway lobster, European hake, red mullet, deep-water rose shrimp
Demersal deep trawl	Bottom otter trawl	blue and red shrimp, giant red shrimp
Passive gears	Set nets, traps, long lines	Norway lobster, European hake, red mullet
Pelagic trawl	Midwater pair trawl	European anchovy, sardine
Purse seine	Purse seine	European anchovy, sardine

See text for references on how species have been assigned to gears and fisheries.

One of the most important results from our analysis is that effort reduction is not accompanied by a concomitant reduction in fishing mortality for all species. Here, we have shown that F and effort are decoupled as effort reductions do not corresponds to reduction in F. Our analysis does not clearly indicate why this has been the case, but the most likely explanation is that nominal effort is not an actual measure of the real effort of the fleet, especially in the case of passive gears (Ribeiro et al., 2015, 2016). It is important to notice that the measures of effort used here are adequate for purse seines and trawling, but less for local, small scale fisheries, which with the same gross tonnage or kw per hour can deploy very different amount of fishing efforts in terms of number or length of gears, and this might risk to invalidate the relationship between F and effort. However, for the species analyzed here, most of the catches are taken by the trawlers and purse seines. For example, small scale fisheries are responsible of around 1% of the catches of small pelagics, < 1% of the catches of blue and red shrimp, giant red shrimp and deep-water rose shrimp, and around 5% of those of Norway lobster. Also at GSA level, catches of small pelagics, Norway lobster, and shrimps are mainly taken by trawlers and purse seines. Only for red mullet and hake, the small scale fisheries take a significant but still minor part of the catches, 15 and 23% respectively, which can be even larger in some GSA (**Table 2**). Thus, we consider that the results of our analysis are robust regard to the way the effort has been measured here. Nevertheless, whatever is the mechanism behind the lack of a relationship between F and effort in the Mediterranean Sea, the results shown

TABLE 4 | Results of the GAMs for each species.

					Predictors				
Model	**Time series**	**Dev. Explained (%)**	r^2	*n*	**GSA**	**Year**	**Effort**	**F trend**	**Average F/F_{MSY}**
Hake*	2004–2014	84.5	0.81	70	<0.001	ns	ns		8.1
Red mullet*	2005–2014	92.9	0.91	78	<0.001	<0.008	ns	↘	3.2
Deep water pink shirmp^	2006–2014	81.3	0.76	50	<0.001	ns	<0.01		2.1
Norway lobster*	2004–2014	95.1	0.93	35	<0.001	ns	ns		2.9
Giant red shrimp^	2006–2014	76.3	0.70	30	<0.001	<0.03	ns	↘	1.7
Blue and red shrimp^	2008–2014	84.6	0.78	20	<0.001	ns	ns		2.5
Anchovy^	2002–2014	87.2	0.84	46	<0.001	ns	ns		1.8
Sardine*	2002–2014	80.4	0.73	46	<0.001	<0.002	ns	↗	2.0

For model details see Section Materials and Methods.
**Log link.*
^Identity link.

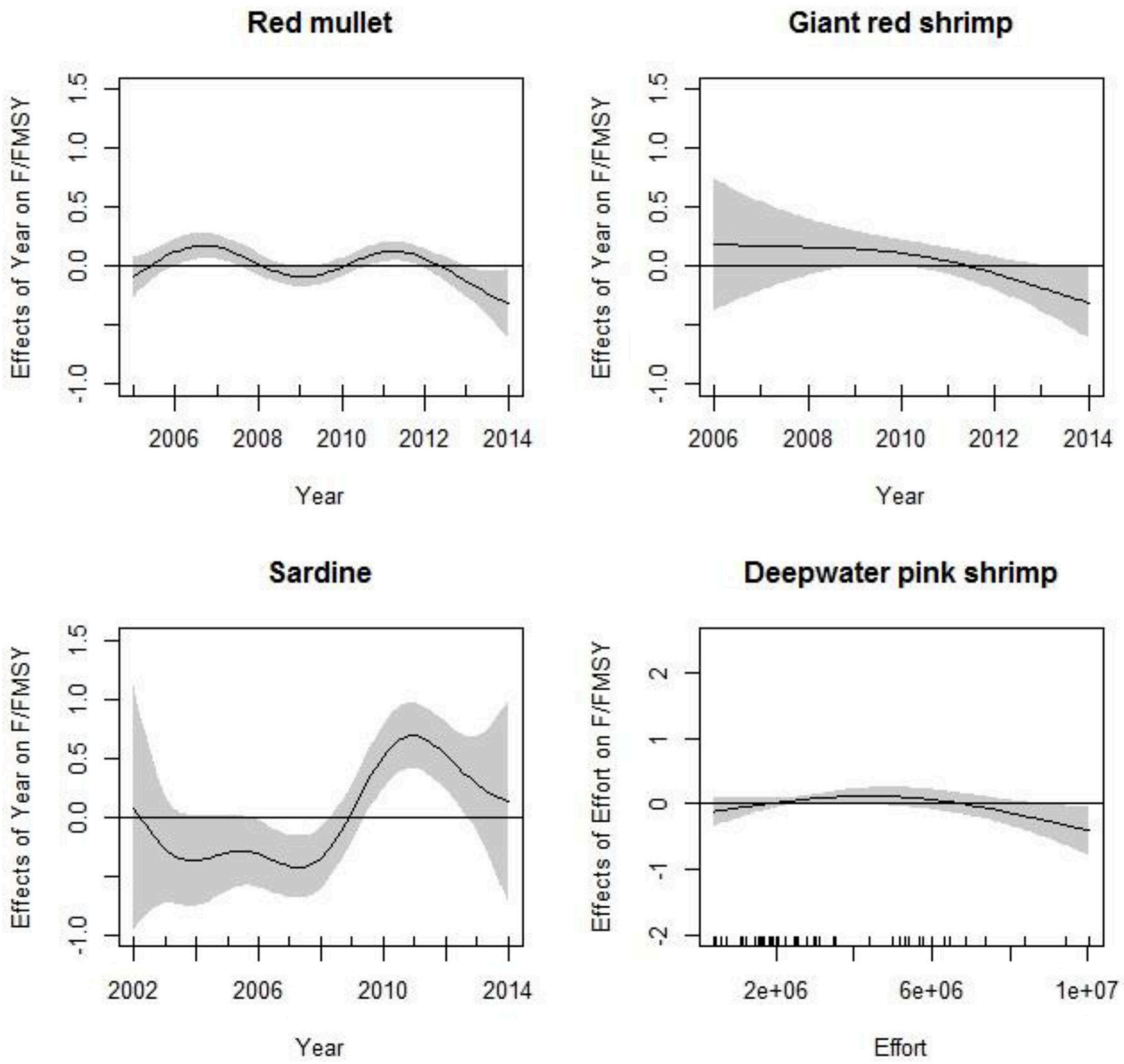

FIGURE 2 | Effect of the predictors (with the 95% confidence intervals) on the ratio between F/F_{MSY} for each model species. Only significant predictors were shown. For model details see Material and methods.

here demonstrated that putative management based mainly on reduction in nominal effort has failed in the Mediterranean Sea and it is most likely that it will most likely fail also in the near future. It is therefore undoubted that alternatives management measures as a TAC based system are necessary if Europe is willing to achieve the objectives of the CFP before 2020 in the Mediterranean Sea.

Another important measure for the management of the Mediterranean Sea stocks within the Mediterranean regulation is the implementation of national MP. Such MPs are allowed by the current Mediterranean Regulation and they are developed at the level of fisheries and/or gear types within national borders. Here, we argue that allowing national management is a clear weakness of the current Mediterranean Regulation as such plans are a very inefficient management measure since they disregard the real geographical distribution of the stocks and fisheries exploiting them. As a matter of fact, most of the stocks are exploited by multiple fisheries and often by different member states. Therefore, it is considered that for stocks shared both in terms of different countries and fleets exploiting them, a fishery management plan needs to include all fleets and countries exploiting the stock (STECF, 2012e). This is likely the reason why management plans in the North East Atlantic have been progressively successful in recent years (STECF, 2014b) while it has not been the case in the Mediterranean Sea (e.g., the multiannual MP for small pelagic in the Adriatic, GFCM/37/2013/1; GFCM, 2013, 2016) and it also clearly highlight another crucial weakness of the current Mediterranean regulation.

Within the framework of an Ecosystem Approach to Fisheries Management, a properly designed and integrated network of different types of MPA could potentially help in achieving

TABLE 5 | Difference (in %) between the scientific catch advice and the realized catches for each year and stock for which a short term forecast was carried out.

Stock	2010	2011	2012	2013	2014
ANE GSA 1		216	−25		
PIL GSA 1		−21	−23		
ARA GSA 6	390	176		70	−3
ARS GSA 9			123	−26	−30
DPS GSA 5		134	58		
DPS GSA 6			−1	−51	81
DPS GSA 9	33	132	88	94	-5
DPS GSA 10		47	54	72	
DPS GSA 18				40	−6
DPS GSA 19					4
DPS GSA 12-16		116	53		
HKE GSA 1			60	−27	418
HKE GSA 5	1,203	763	306	54	
HKE GSA 6		340	248	52	
HKE GSA 7		86	97	1,450	552
HKE GSA 9	352	259	289	91	
HKE GSA 10	128	172	219	58	374
HKE GSA 11			1,014	115	−66
HKE GSA 19					191
MUT GSA 6		54	254	47	
MUT GSA 7	174	140	−3	159	102
MUT GSA 9		72	31		
MUT GSA 10		−18	132	91	
MUT GSA 11	282	14	51		
MUT GSA 17					281
MUT GSA 18				221	147
MUT GSA 25	92	−19			
NEP GSA 5		170			
NEP GSA 6			294	163	
NEP GSA 9	89	55	83	41	

*See **Table 1** for references.*

a better exploitation pattern and the MSY sustainability target. However, the extension of MPA in the Mediterranean Sea is still rather limited (http://www.eea.europa.eu/data-and-maps/figures/regional-seas-surrounding-europe-and-2) and thus MPA are likely to contribute only little to the current management of Mediterranean stocks. It is also unquestionable that the complexity of the Mediterranean fisheries, with a large number of small vessels operating at a small spatial scale in very local fisheries, and the diverse cultural, social and economic characteristics of the countries sharing the resources pose significant challenges to sustainable management of Mediterranean marine resources (Piroddi et al., 2015). However, here we shown that even stocks mainly caught by trawlers and purse seines within EU waters, are fished not in accordance with the CFP MSY target and that management of these stocks is ineffective to control their level of exploitation. Moreover, these stocks have a central role in management resolutions as they are the key species of future Mediterranean management plans.

Vasilakopoulos et al. (2014) argued that the difference in fisheries management performances between the Northern and the Southern part of Europe pattern might be explained not only by the more sophisticated management regime and better compliance and enforcement of the North East Atlantic, but also by the socio-economic complexity and less effective governance system in the southern Europe (Smith and Garcia, 2014). Here, we showed instead that major reasons for the alarming situation of Mediterranean Sea stocks can be found in the ineffectiveness of the putative effort reductions to control fishing mortalities, the continuous non-adherence to the scientific advice, and the existence of ineffective national management plans as a primary management measure. The European CFP has failed to achieve MSY before 2015 for the Mediterranean Sea and will face large difficulties to reach MSY and MSFD targets before 2020 under the current management regime.

AUTHOR CONTRIBUTIONS

All authors listed, have made substantial, direct and intellectual contribution to the work, and approved it for publication.

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REVIEW
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Controls of Multiple Stressors on the Black Sea Fishery

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Black Sea is one of the most severely degraded and exploited large marine ecosystems in the world. For the last 50 years after the depletion of large predatory fish stocks, anchovy (with the partial contribution of sprat) has been acting as the main top predator species and experienced a major stock collapse at the end of 1990s. After the collapse, eastern part of the southern Black Sea became the only region sustaining relatively high anchovy catch (400,000 tons) whereas the total catch within the rest of the sea was reduced to nearly its one-third. The lack of recovery of different fish stocks under a slow ecosystem rehabilitation may be attributed, on the one hand, to inappropriate management measures and the lack of harmonized fishery policy among the riparian countries. On the other hand, impacts of multiple stressors (eutrophication, alien species invasions, natural climatic variations) on the food web may contribute to resilience of the system toward its recovery. The overfishing/recovery problem therefore cannot be isolated from rehabilitation efforts devoted to the long-term chronic degradation of the food web structure, and alternative fishery-related management measures must be adopted as a part of a comprehensive ecosystem-based management strategy. The present study provides a data-driven ecosystem assessment, underlines the key environmental issues and threats, and points to the critical importance of holistic approach to resolve the fishery-ecosystem interactions. It also stresses the transboundary nature of the problem.

Keywords: Black Sea, climatic variability, ecosystem, fishery, multiple stressors

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INTRODUCTION

At global scale, evidence is unequivocal for multitude of changes on ocean biogeochemical cycles and ecosystems due to ocean warming, acidification, and deoxygenation in response to the rising atmospheric CO_2 levels (Hoegh-Guldberg and Bruno, 2010; Doney et al., 2012; Bopp et al., 2013; Poloczanska et al., 2013). Coastal, shelf, and semi-enclosed seas providing important economic resources experience additional stressors arising from the local/regional natural climatic variations, eutrophication, eutrophication-induced changes (such as acidification, de-oxygenation, loss of biodiversity, degradation of food web, etc), overfishing, and alien species invasion (Boldt et al., 2014). For these ecosystems, both CO_2 and non-CO_2 related stressors acting together have potential to alter trophic structure, food-web dynamics, energy and material flows, and biogeochemical cycles and thus impact considerably the ecosystem services for humans, as in the case of Baltic Sea (Niiranen et al., 2013; Jutterström et al., 2014). The Black Sea offers one of the best examples for how the multiple stressors act together to alter its ecosystem structure through regime shifts (Daskalov et al., 2007; Oguz and Gilbert, 2007; Oguz and Velikova, 2010; Llope et al., 2011; Akoglu et al., 2014).

The Black Sea is a nearly enclosed and zonally elongated basin with the zonal dimension of about 1,200 km and the meridional dimension varying from 500 km on the western side to 250 km toward the eastern side (**Figure 1**). It has a limited interaction with the Aegean Sea through the Turkish Straits System. Its main bathymetric feature is the presence of a narrow shelf (generally less than 20 km) and steep topographic slope (generally less than 30 km) around 2,000 m deep interior basin (**Figure 1**). The northwestern part of the sea characterized by a fairly wide shelf and its connection to the deep western basin through a wider topographic slope zone. The width of the western shelf gradually reduces toward south and finally terminates to the east of the Bosphorus Strait exit region (**Figure 1**). The Black Sea receives fresh water inflows all around the basin but the important ones discharge into the northwestern coastal waters. The River Danube being one of the largest rivers in Europe introduced dramatic effects on the Black Sea ecosystem.

The most recent in-depth ecosystem assessment has been provided by the State of the Environment Report published by the BSC (2009) and the fishery—specific assessment by FAO (2016). The present study complements them by providing a data-driven holistic ecosystem assessmentthat synthesizes the available data used for the BSC assessment, provides an overview picture on the transformations of the Black Sea ecosystem since the middle of the previous century, and describes the changes in fishery characteristics in harmony with the impacts of multiple environmental stressors. Gathering historical data and synthesizing existing knowledge may help to reconstruct historical baselines for understanding individual and cumulative impacts of disturbances on the ecosystem, especially over long—(e.g., decadal)—time scales. The objective is to provide a scientific basis and justification for an implementation of ecosystem level management strategy to improve not only its fishery but also general health of the ecosystem as an alternative to the present approach of managing fish species independently.

Following the major characteristics features of climate variability and the past and present states of fishery, the present study describes the characteristic features of nutrient over enrichment and alien species invasions. Then, it describes the major changes in ecosystem state during the last 50 years. Finally, it identifies the major knowledge gaps in relation to ecosystem-level management strategies (what to do and how to proceed forward) and gives the concluding remarks.

MATERIALS AND METHODS

The SST comprises monthly mean data compiled by Hadley Centre, UK Met Office (http://badc.nerc.ac.uk/data/hadisst). It consists of *in situ* measurements as well as Advanced Very High Resolution Radiation (AVHRR) satellite products (Rayner et al., 2003). The mean Cold Intermediate Layer (CIL) temperature data are given by Belokopytov (2011). This data set yields based on the monthly mean data constructed from all the available measurements performed within the interior part of the basin by averaging its values less than 8°C. The yearly landing data on the basis of countries report were obtained from the Sea Around Us project (SAUP) database (http://www.seaaroundus.org). In the SAUP database the Soviet Union catches prior to 1990 comprised the sum of contributions from Ukrainian, Georgian, and Russian catches. The same aggregation is also applied here after 1990 for representing the cumulative landing for the northern and eastern regions. Similarly, the Romanian and Bulgarian landings are aggregated for representing total fishery of the western region. The Turkish fleet was able to operate in Georgian waters after 1995 (Knudsen and Toje, 2008). Therefore, some of the catch realized in the Georgian EEZ is included in the Turkish landings statistics. Anchovy spawning stock biomass data after 1990 is taken from STECF (2015) whereas its earlier part is provided by Shlyakhov and Daskalov (2009). All the other data sets are provided by the Black Sea Commission data base that was used for the preparation of the State of the Environment Report (BSC, 2009) and may be made available to readers by the author up on request. Chlorophyll-a concentrations are retrieved from the monthly composite ocean color satellite data; the SeaWiFS sensor prior to 2002 (9 km resolution) and the MODIS sensor (4 km resolution) afterwards.

CONTROL OF THE ECOSYSTEM BY INDIVIDUAL STRESSORS

Stressor 1: Climatic Variations

The physical characteristics of the upper layer water column above the base of the permanent pycnocline experienced distinct decadal-scale oscillations (Oguz et al., 2006; Piotukh et al., 2011). The sea surface temperature (SST) is usedhere as a proxy for describing climatic variability. It indicates a relatively mild cooling phase (0.5°C) during 1960–1980 and a subsequent more pronounced cooling phase identified by the winter (December–March) mean sea surface temperature (SST) changes as high as 1.5°C during 1980–1993 (**Figure 2**). Similar variations are also observed in the summer-autumn (May–November) mean subsurface CIL temperature field (**Figure 2**). They are followed by an equally pronounced warming phase during 1993–2014. They imply a clear signal of climatic changes within the upper 100 m water column above the permanent pycnocline. The climate-induced temperature changes are related to strengthening of the NAO; its positive phase resulting in colder, drier, and more severe winters contrary to the simultaneous wetter, warmer, and milder winters over the northwestern Europe and the Eastern North Atlantic Ocean (Oguz et al., 2006). The subsequent warming trend starting by 1993 up to 2001 increases the SST and CIL temperature back to their former levels prior to the 1980. Afterwards, both SST and CIL temperature undergoes to a decadal scale oscillation with an amplitude of ∼1.5°C between the minimum at 2005–2006 and the maximum at 2010–2011, followed by a decreasing trend. The important point to note here is that such pronounced decadal scale temperature variations after 1980 match with the intensification of eutrophication and fishery and large population increase of the alien species *Mnemiopsis leidyi*. The temperature changes may introduce strong impacts on the Black Sea ecosystem through direct changes in species physiological characteristics and indirectly by the changes in the flow, stratification and mixing characteristics.

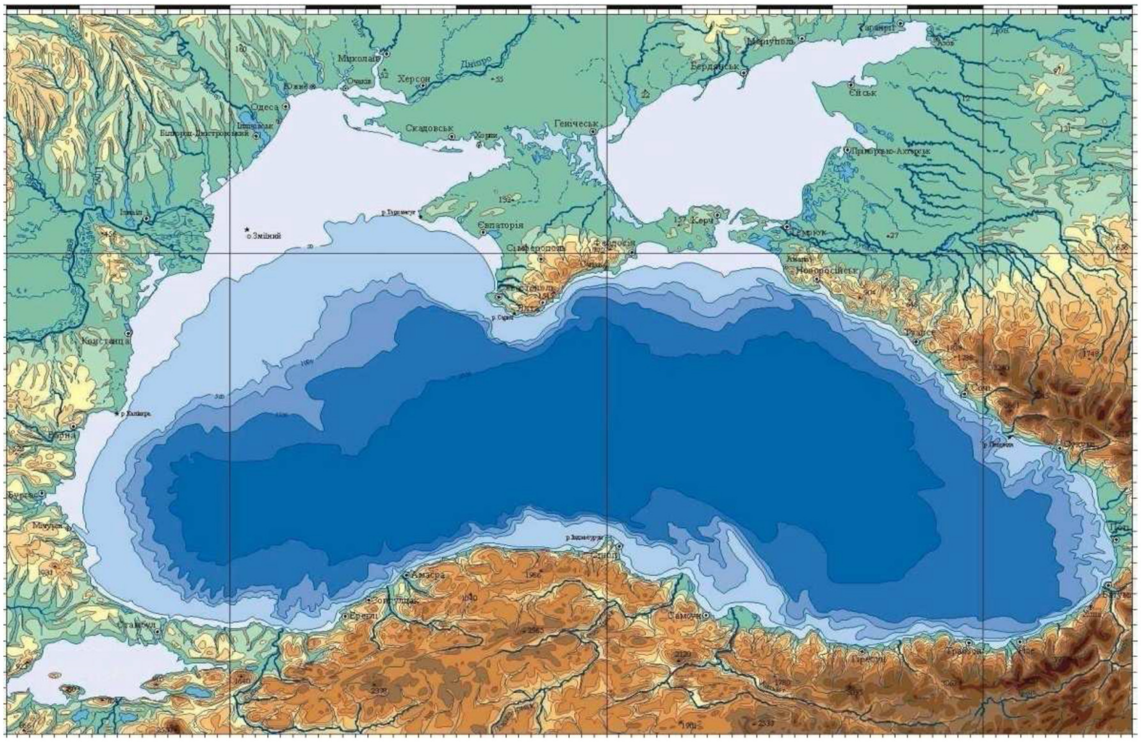

FIGURE 1 | The location and bathymetry of the Black Sea.

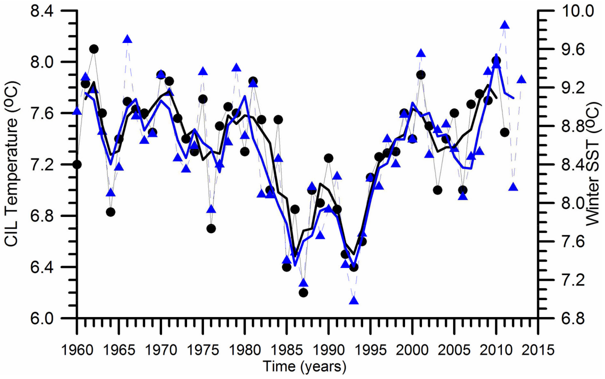

FIGURE 2 | Long term variations of the winter (December-March) mean sea surface temperature and the summer-autumn (May-November) mean Cold Intermediate Layer (CIL) temperature below the seasonal thermocline. The thin lines with symbols refer to the original data whereas the thick lines represent their smoothed variations by three point running averaged.

Stressor 2: Fishery Overexploitation

According to the long-term data (**Figure 3A**), the total fish landing reduces from 300 ktons (1 kton = 1,000 tons) to 100 ktons during the 1950s. The fish resources were exploited primarily by the former USSR (Georgia + Russia + Ukraine) as their total landing declined from more than 200 ktons to less than 50 ktons within a decade. The former USSR fishery first exploited the large and middle-size valuable predatory species including marine mammals, sturgeon, tuna, bonito, turbot, large horse mackerel, Black Sea mackerel prior to 1950s (Prodanov et al., 1997), and then started to exploit small pelagics with the Mean Trophic Level (MTL) index around 3.1–3.2 (Oguz et al., 2012a). On the other hand, the size of total Turkish landing was limited to ∼50 kton level during the same period (**Figure 3A**), but the Turkish fishery primarily focused on the medium and large predatory fish groups identified by the MTL range between 3.4 and 3.8 (Oguz et al., 2012a). The Bulgarian+Romanian contribution to the total landing has always remained below 50 ktons (**Figure 3A**). The fishery, therefore, has been exploited severely in terms of the landing capacity, fish size, and diversity. As a result, the small pelagics became the only top predator group with a relatively low total landing size of 150 ktons over the entire basin toward the end of 1960s.

The total landings increased abruptly starting by the early 1970s to the range of 200–300 ktons within the former USSR countries and 500 ktons in Turkey. The October anchovy standing stock estimates (i.e., at the begining of the fishing season) increased drastically from ∼300 ktons in the 1960s to 1.5 million tons in the late-1970s (Prodanov et al., 1997). A more conservative increase up to 700 ktons was suggested later by Shlyakhov and Daskalov (2009). Soon after the peak landing phase of the early1980s the USSR landing within the north-northeastern basin as well as the Romanian + Bulgarian landing within the western basin started declining gradually (**Figure 3A**). Nevertheless, the high level Turkish landing (around 500,000

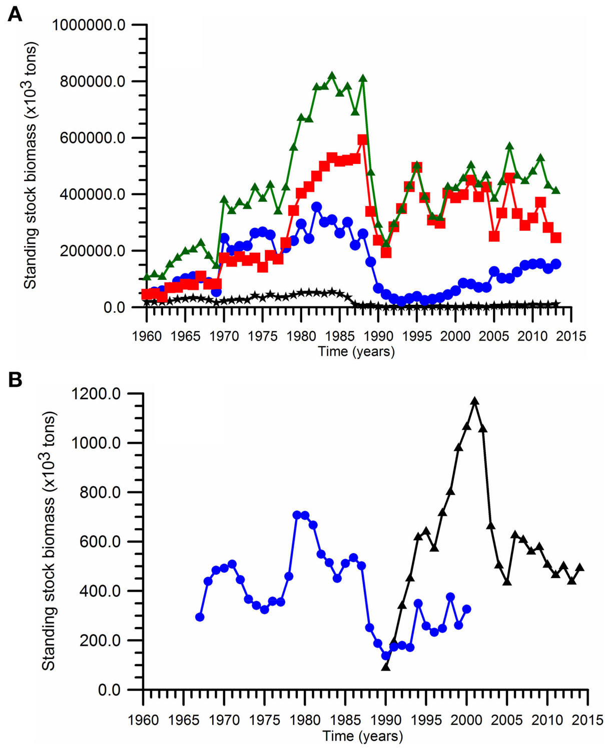

FIGURE 3 | Time series of (A) the annual landings over the entire basin (▲), the Turkish waters (■) (the southern sector of of the Black Sea), and Bulgarian and Romanian waters (⋆) (the western sector), Georgia+Russia+Ukraine waters (·) (the northern+eastern sector), and **(B)** of the annual anchovy spawning stock biomass estimated by Shlyakhov and Daskalov (2009) (·) and by STECF (2015) (▲).

tons) within the southern basin was able to prevail until the end of 1980s, after which it dropped abruptly to its minimum level of ~200,000 tons at 1990–1991 (**Figure 3A**). While this catch size was referred to as the collapse, it was in fact comparable to the maximum sustainable yield of the system (Oguz et al., 2012a). Afterwards, the former USSR landing remained around 10% level of their previous phase during the 1990s and increased up to 150 ktons subsequently, whereas the total western landing was negligibly low (**Figure 3A**). On the other hand, the Turkish exclusive economic zone was able to maintain the mean anchovy catch at 368,000 (±74,000) tons for 1992–2010. This value was somewhat lower than the pre-collapse values but still comparable to twice of the maximum sustainable catch (Oguz et al., 2012a). The presence of oscillations in the landing data during this phase may likely indicate an unstable character of the Turkish fishery. The SAUP data base also provides an alternative catch data by the inclusion of unreported catch estimates. This alternative data set suggests 100% percent difference between the reported and actual amounts of fish caught and the overall catch then amounts to ~800,000 tons after 1995. The catch size during the last two decades is comparable to that given for the transitional period of the 1970s between the pre- and intense-eutrophication phases. But they differ in terms of spatial catch distributions.

Stressor 3: Nutrient Overenrichment

Substantial increase in nutrient concentrations of the upper layer water column throughout the sea was a striking feature of the Black Sea ecosystem in the 1970s and the early-1980s. These changes were caused by the implemention of a massive fertilizer consumption in agriculture in the former Soviet Union and Warsow Pact countries to compensate the food loss due to the collapse of fishery (Mee, 2006). This led to an increase in the total nitrogen (phosphorus) emission in the River Danube catchment basin from about 400 (40) kt yr^{-1} in the 1950s to 900 (>100) kt yr^{-1} in the 1980s.

Approximately 80% of the total anthropogenic nitrogen flux was supplied by the River Danube whereas the rest was provided by the rivers discharging along the northwestern coast (Dniepr, Dniester, Bug) and along the southern coast (**Figure 1**). However, due to the lack of systematic nutrient measurements at the Danube discharge sections during the 1970s and the early 1980s, it was not possible to monitor precisely the magnitude of anthropogenic-based nutrient enrichment during its initial phase. Nevertheless, the scattered measurements performed near the Chilia discharge point of the River Danube (at Vilkova) indicated an average DIN concentration of 56.6 μM for 1948–1960 (the pre-eutrophication phase), increasing subsequently to 118.9 μM in 1977–1985 and 156.1 μM in 1989–1992. The latter was roughly half of the mean DIN value of 310 μM measured at the Sulina discharge point during the same period in addition to a drastic rise of DON concentration from ~50 to ~350 μM. Consequently, the sum of organic and inorganic dissolved nitrogen concentration at the end 1980s reached 500 μM that implies a nearly five-fold increase with respect to the pre-eutrophication conditions. A similar increase was also noted within the Romanian and Ukranian sectors of the northwestern shelf during the 1970s with the annual mean surface nitrate and phosphate concentrations more than 20 and 3 μM, respectively (**Figure 4A**).

Following the collapse of centrally-planned economy within the former Soviet Union, nitrogen and phosphorus fertilizer consumptions reduced to 1.5 and 0.5 mt yr^{-1}, respectively, during the early 1990s (Mee, 2006). With the additional contributions by the closure of ecologically ineffective large animal farms (agricultural sources) and the introduction of phosphorus-free detergents and the improved nutrient removals at treatment plants, the Danube P-PO_4 load reduced sharply from ~30 kt yr^{-1} to about 10 kt yr^{-1} (**Figure 4B**). The decrease in the Danube DIN load was more substantial; from around 700 kt yr^{-1} to less than 200 kt yr^{-1} (**Figure 4B**). 90% of the DIN load was provided by N-NO_3. They resulted in nitrate and phosphate concentrations less than 5 and 0.5 μM, respectively, within the shelf. DON concentrations, on the other hand, preserved its former high levels. The nutrient fluxes from the Dniepr and Dniestr Rivers into the NWS are an order of magnitude smaller during both the intense and post eutrophication phases, and introduce only local effects in the vicinity of their discharge regions.

Benthic nutrient fluxes were found to be particularly high in the vicinity of discharge zones, but decreased almost by an order of magnitude toward the shelf edge depending on intensity of

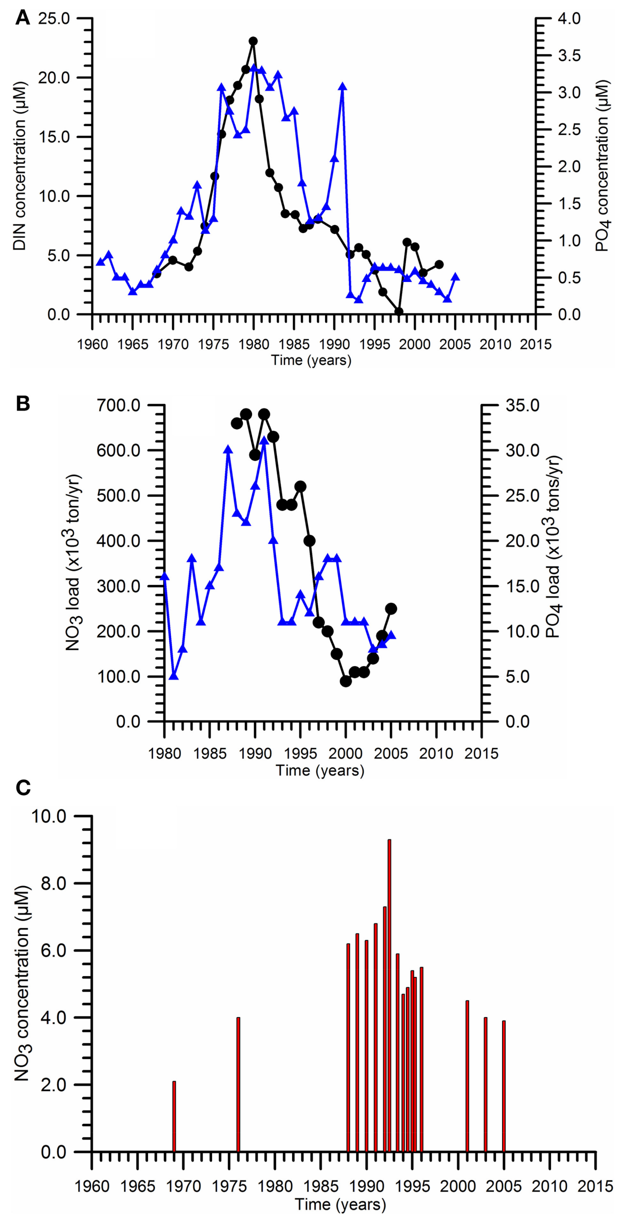

FIGURE 4 | Temporal variations of (A) the annual mean surface nitrate (■) and phosphate (•) concentrations within the northwestern (Romanian and Ukranian sectors) coastal-inner shelf waters, **(B)** River Danube annual dissolved inorganic nitrogen (DIN) and phosphate (P-PO4) loads, **(C)** maximum nitrate concentrations measured at the chemocline of interior deep basin.

primary production, vertical mixing, and water depth (Gregoire and Friedrich, 2004). The estimate of total ammonium flux of 250 ktons yr^{-1} turns out to be higher than the post-eutrophication value of the River Danube DIN flux. Similarly, the corresponding total phosphorus flux over the NWS amounts to 50 ktons yr^{-1}, which is also much higher than that provided by the River Danube. The sediment data, therefore, imply that the benthic system still keeps the memory of past eutrophication and the benthic nutrient recycling mechanism constitutes an important factor for sustaining high productivity especially in shallower parts of the NWS.

The additional nutrient inputs from the atmospheric wet and dry depositions are not known precisely, but the estimated atmospheric DIN and DIP loads of 32.5 ktons yr^{-1} and 2.1 ktons yr^{-1}, respectively, are much smaller than the corresponding riverine loads over the annual time scale (Medinets and Medinets, 2012). Nevertheless, episodic high deposition events into nutrient depleted surface waters during late spring-summer may occasionally prevail over the basin. The model estimated atmospheric nutrient inputs were, on the other hand, much lower and less than 10% of the river inputs (cited by Artioli et al., 2008).

The basinwide response of increased nutrient supply by the northwestern rivers after the early 1970s was their accumulation within the chemocline zone of the upper layer as suggested by the rise of the subsurface nitrate peak from roughly 2–3 μM prior to the enrichment phase to 6–8 μM afterwards over the entire basin (**Figure 4C**). As the increased nutrient supply built up nutrients more effectively in the chemocline zone (located immediately below the euphotic layer), these nutrients were made available to the euphotic layer more effectively under strong winter climatic conditions. This peak was slightly eroded after 1990s and reduced to 4–5 μM in response to the reduction in anthropogenic-based nutrient reduction loads. A similar structure continues to maintain today (Tugrul et al., 2014).

Stressor 4: Invasion by Alien Gelatinous Species

As the environmental deterioration progressed in the Black Sea, opportunistic, and gelatinous species started dominating the food web (Kovalev and Piontkovski, 1998). The jellyfish *Aurelia aurita* being less than 50 g m^{-2} before the 1960s became a major gelatinous predator species during the eutrophic ecosystem of early-1980s with typical biomass around 500 g m^{-2} and then declined to 100 g m^{-2} toward the end of 1980s (**Figure 5A**). The increase in *Aurelia* biomass might have been associated with the overfishing and removal of mackarel, which was a main predator of *Aurelia* in Black Sea (Arai, 2001). Following the massive population increase of *M. leidyi* at the end of 1980s, the *Aurelia* biomass became comparable to the pre-eutrophication phase, because of better competitive advantage of *Mnemiopsis* consuming preys.

Following its accidental introduction into the Black Sea from its native habitat along the eastern coastal waters of the North and South America continents in the early 1980s (Purcell et al., 2001), *Mnemiopsis* was observed in different parts of the Black Sea during 1982–1987. Its average biomass reached 1 gC m^{-2} (≈ 1.0 kg ww m^{-2}) during summer-autumn 1988 in the eastern basin (Shiganova et al., 2014), and then suddenly acquired an outbreak with the biomass level up to ~3.0 gC m^{-2} in coastal waters during 1989–1990 (**Figure 5A**). Soon after the population outburst phase (1988–1992), *Mnemiopsis* abundance and biomass stabilized at lower levels, but acted as the main predator on the food web structure. Its impact on the fodder zooplankton is 3–4 fold reduction in its biomass (**Figure 5A**).

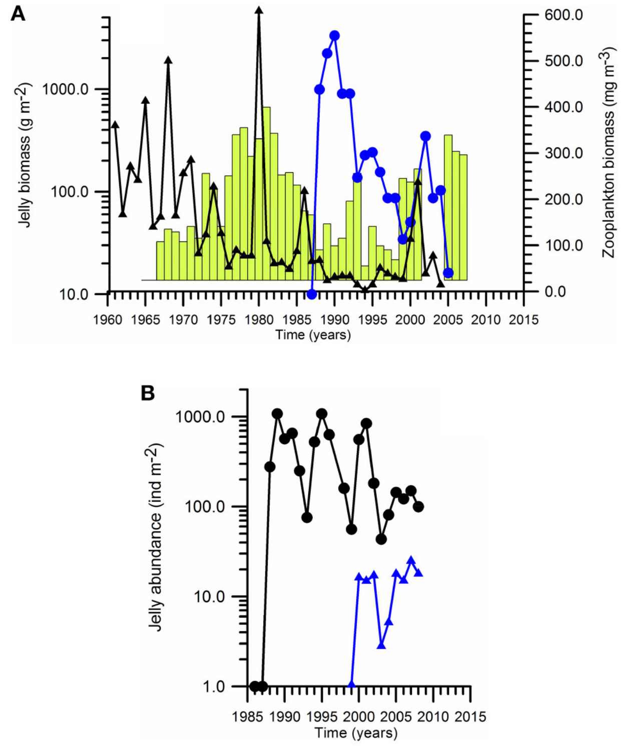

FIGURE 5 | Long-term biomass changes of (A) *Aurelia* biomass (vertical bars), *Mnemiopsis* biomass (•) and edible zooplankton biomass (▲), and **(B)** *Mnemiopsis* abundance in August (•) and *Beroe* abundance in September (▲) in the northeastern shelf-slope region.

The ctenophore species *Beroe ovata* entered accidentally at 1998 and started predating on *Mnemiopsis* population and reducing its biomass and abundance (**Figure 5B**). Starting by 1999, *Mnemiopsis* biomass was reduced considerably except the late summer-autumn at its peak reproduction phase (Vinogradov et al., 2000). Nevertheless, *M. leidyi* can be still observed at high concentrations in the northwestern and western coastal regions with respect to its lower abundance elsewhere. As a result, the predation pressure of *Mnemiopsis* on zooplankton became limited to the late-summer and autumn months. The nich vacated by *Mnemiopsis* was, then, occupied by an increase in the jellyfish *Aurelia* biomass to the range of 200–500 g m^{-2} (**Figure 5A**). The other gelatinous species *Pleurobrachia* has never played a predominant role on the food web structure. As a matter of fact, the present reduced jelly biomass/abundance is still higher than the corresponding values in the Mediterranean and Baltic Seas. Among the 63 LMEs, the Black Sea attains the highest Jellyfish Index value which is twice higher than the values of other European Seas (Brotz et al., 2012).

Stressor 5: Frontal and Mesoscale Circulation Features

Gucu et al. (2016) recently noted a non-migratingcharacter of the anchovy stocks within the southern Black Sea that utilized local food resources confined within coastal hydrographic features associated with the rim current. In fact, the narrow peripheral zone of the Black Sea appears to be always more productive at all trophic levels than the interior basin. The field observations performed in the northeastern Black Sea (i.e., almost 1,000 km away from the main source of eutrophication) documented relatively high concentrations of phytoplankton and zooplankton species/groups within the shelf-slope zone with respect to further offshore (Vinogradov et al., 2011; Mikaelyan et al., 2013; Arashkevich et al., 2014; Shiganova et al., 2014, and others). The fish eggs and larvae surveys (Niermann et al., 1994; Kideys et al., 1999; Gucu et al., 2016) and abundance and biomass measurements of gelatinous species (Mutlu, 2009) along the southern Black Sea showed their patchy distributions with higher concentrations closer to the coast. The primary production required (i.e., ecological cost of the catch) in this region was also found to be roughly twice of its basin-averaged maximum sustainable value (Oguz et al., 2012a) indicating higher phytoplankton production with respect to the interior basin. Furthermore, the annual mean surface chlorophyll-a (Chl-a) concentrations around the basin, provided by the satellite ocean color data, always exceeded those of the interior with some interannual variability (**Figure 6A**).

The mechanisms promoting relatively high phytoplankton population and thus supporting more effective zooplankton, small pelagics fish, and larvae populations around the periphery with respect to the cyclonic domes of the interior basin remained unexplained quantitatively to date. The nutrient enrichment from the rivers around the basin alone appears to be too low to maintain such a persistent basinwide feature except the Northwestern shelf. The recent modeling study by Oguz (submitted) relates this feature to the frontogenesis mechanism of the Rim Current circulation arising from its non-linearity and collapse of the along-front geostrophic balance (Mahadevan, 2016). The resulting ageostrophic cross-frontal vertical circulation cell then provides high vertical velocities (∼10–50 m d^{-1}) at meander crests on the less dense coastal anticyclonic sides of the front. They supply nutrients effectively into the euphotic zone relative to the cyclonic offshore side and to produce locally high plankton biomass. The transports of biota and nutrients by the rim current around the basin and offshore into the interior cyclonic cell by mesoscale features then sustain a year around relatively high phytoplankton biomass around the basin (**Figure 6B**). The eddy-induced horizontal and vertical nutrient transports and diapycnal turbulent mixing further contribute to the enhancement of plankton production.

CUMULATIVE EFFECTS OF MULTIPLE STRESSORS ON THE ECOSYSTEM AND FISHERY

The Black Sea ecosystem experienced three alternative states. The "*pre-eutrophication*" state prior to the early 1970s represented relatively mild winters, low anthropogenic loads from rivers, a modest level of phytoplankton biomass, weakening of their top-down pressure due to the loss of piscivours, and over-exploitation of its fishery resources. The transition toward the development of

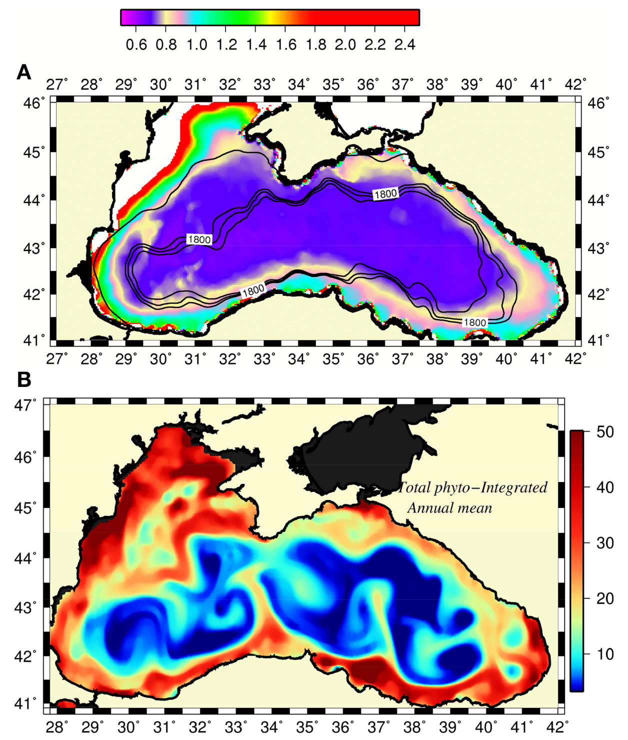

FIGURE 6 | (A) Long-term (2002–2015) mean surface chlorophyll a concentration distribution (mg Chl m^{-3}) with the margin topography superimposed by 1,800, 2,000, and 2,200 m isobaths, **(B)** annual-mean euphotic-layer integrated phytoplankton biomass distribution (mmol N m^{-2}) provided by model simulations. The narrow strip of white color along the western coast designates chlorophyll concentration greater than 2.5 mg m^{-3}.

more productive "*intense eutrophication*" state during the 1970s (the first regime shift) was accomplished by the loss of predator controls and over-enrichment of the upper layer water column due to eutrophication and climate-induced cooling. The period after the early 1990s constitutes the "*post-eutrophication*" state.

Intense Eutrophication State

Three-four fold increase of the chemocline layer nitrate concentrations over the entire Black Sea during the decadal climatic cooling phase (i.e., more severe winter climatic conditions) increased phytoplankton biomass up to 10-folds within the northwestern shelf and the interior basin during the 1980s. The euphotic zone-integrated mean phytoplankton biomass within the central and eastern basins during summer-autumn increased from about 2–3 g m^{-2} before 1970s to 10 g m^{-2} in the 1970s and 20 g m^{-2} in the 1980s (**Figure 7A**). Cold winters imply greater vertical turbulent and advective fluxes of nutrients into the euphotic zone from the subsurface waters that then may support stronger spring and subsequent summer blooms. These features may explain the cause of relatively high surface phytoplankton biomass (>10 g m^{-3}) maintained throughout the 1980s and the early 1990s over the Ukrainian, Romanian and Bulgarian shelf waters. The deep interior basin was also exposed to a similar increase in phytoplankton biomass.

One of the critical features of the eutrophic Black Sea during the 1980s has been the development of a complementary food chain toward the dead-end opportunistic species (e.g., *Noctiluca scintillans*) and jellyfish in addition to the classical pathway toward small pelagics. Because they were more competitive on grazing of zooplankton, they were able to divert more energy from the system and thus limiting the efficiency of the classical food web. For example, the biomass of heterotrophic dinoflagellate species *Noctiluca,* as a voracious predator with diverse diet including a wide range of phytoplankton, bacteria, detritus, eggs, and naupliar stages of copepods was increased along the western coastal waters by an order of magnitude roughly from 100 mg m^{-3} in the 1970s to about 1,000 mg m^{-3} in the 1980s (**Figure 7B**).

The Black Sea ecosystem produced higher edible zooplankton biomass during the eutrophic phase of 1980s with respect to the pre-eutrophication phase. But, its biomass in the northwestern shelf declined steadily later in the 1980s with (**Figure 5A**) due to heavier predation by small pelagics and gelatinous carnivores and replacement by smaller and less valuable species due to degradation of the food web structure. The edible zooplankton biomass within the eastern basin did not show any particular trend; instead it fluctuated within the range of 5–15 g m^{-2} during the same period (**Figure 7A**).

The ecosystem state experienced the second regime shift a decade later. It was characterized by the collapse of small pelagic fish stocks due to their over-harvesting and simultaneous impact of population outburst of the gelatinous carnivorous *M. leidyi* at the end of 1980s. As substantiated by the modeling studies (Oguz et al., 2008), the simultaneous anchovy collapse and *Mnemiopsis* outburst was possible in the eutrophic ecosystems under favorable climatic conditions promoting excessive nutrient enrichment of the euphotic layer from the chemocline. Beyond its a particular limit, the nutrient flux starts supporting more favorably the growth of gelatinous populations instead of its competitor fish species. Physiologically, a growth and reproduction advantage of *Mnemiopsis* relative to the native gelatinous species *Aurelia,* and advantage of food consumption in respect to anchovy promote its growth excessively without saturation. Therefore, their stronger predation pressure on anchovy eggs and larvae caused reduction in anchovy recruitment biomass and weakening its competition against *Mnemiopsis*. These mechanisms together with high anchovy harvesting inevitably caused recruitment failure and the stock collapse of anchovy. Akoglu et al. (2014) also pointed to the synergistic roles of resource competition and fishery exploitation for the anchovy-*Mnemiopsis* regime shift using an indicator-based mass balance food web analyses. An important implication of these modeling studies is to link the anchovy collapse to the *Mnemiopsis* population under the conditions of high nutrient enrichment of the system. This mechanism opposes to the alternative view that, based on subjective grounds from the catch data, links the fishery collapse solely to their overexploitation. It also opposes to another hypothesis that relates the catch decline not to the collapse of stocks but their translation, for some

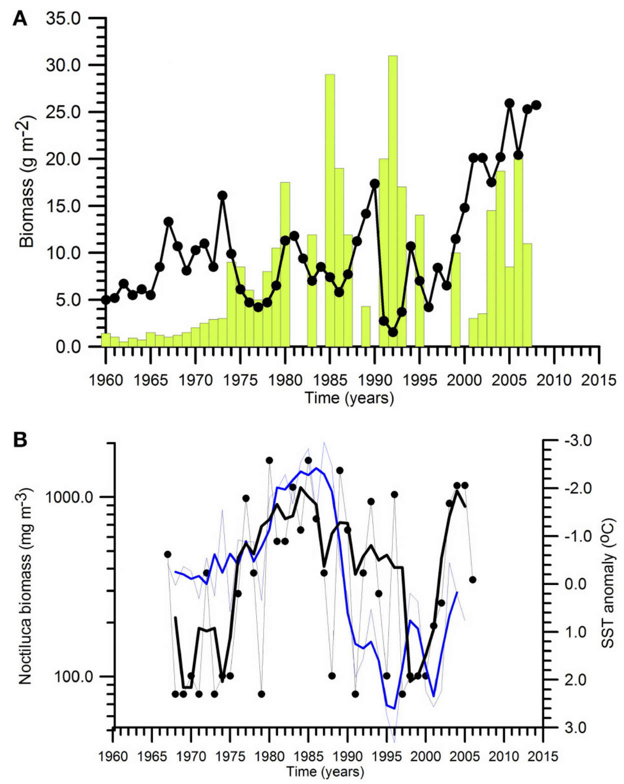

FIGURE 7 | Temporal variations of (A) summer-autumn mean phytoplankton biomass integrated over the euphotic zone (vertical bars), and zooplankton biomass (•) for the northeastern part of the Black Sea, **(B)** *Noctiluca scintillans* biomass (•) and annual-mean SST variations at the coastal station Galata along the Bulgarian coast.

unknown reasons, away from their regular fishing grounds (Gucu et al., 2017).

Post-eutrophication State

Starting by the early 1990s, the last two decades are referred to as the "*post-eutrophication*" state characterized by the decreasing nutrient loads and nitrate accumulation at the chemocline zone, the climatic warming trend, and the absence of fishery except in the southern basin. In the early years of the post-eutrophication phase (i.e., the 1990s) *Mnemiopsis* introduced a major stress on the food web and acted as the major top predator in many regions in the absence of small pelagic stocks. The phytoplankton and *Noctiluca* biomass also decreased during the post-eutrophication phase in aggrement with the reduced antropogenic nutrient supply and negative effect of climatic warming conditions (**Figures 7A,B**). The reduced top-down and bottom-up controls might have altered food web functioning the details of which is not exactly known due to the lack of systematic observations.

By the introduction of *B. ovata* to the Black Sea at the end of 1990s, the predation pressure of *Mnemiopsis* became limited to the autumn period, and the reduction in its biomass turned out as an increase in the catch data, as noted by its twice higher USSR values for the northern-northeastern basin (**Figure 3A**). On the other hand, the absence of any increase on the catch data within the western part may be related to the ongoing strong *Mnemiopsis* control.

An important feature of the post-eutrophicatipon phase is the shift of the annual phytoplankton bloom structure from its former double-peak form (a relatively strong March–April peak and a secondary peak in November-December) prevailed during the intense eutrophication phase under severe winters to a single-peak form encompassing November–February period but more predominantly during November–December (**Figure 8**). The cause of this shift is not known so far but the persistence of relatively warm climatic regime and a change in the predatory control after the introduction of *Beroe* may contribute to it. Another notable feature is higher annual mean chlorophyll concentrations and stronger winter peaks during warm years and vise versa for cold years (**Figure 8**). This feature was explained by a more limited offshore spreading of productive coastal waters toward the interior basin during cold years due to the intensification of the rim current circulation and weakening of its mesoscale variability (Kubryakov et al., 2016). On the contrary, more intense mesoscale variability of the rim current circulation in mild years may promote stronger bottom-up food supply to higher trophic levels and support higher anchovy stock biomass as compared to those in cold years. This assertion, however, needs to be quantified by biophysical modeling studies. The climate impact on phytoplankton biomass is also depicted on the interior basin phytoplankton biomass variations in the form of a declining trend during the warming phase of the 1990s and increasing trend during the subsequent cooling phase (**Figure 7A**).

The main ecosystem properties appear to differ considerably between the western, southern, and northeastern regions (Oguz et al., 2012b). The pelagic food web structure of the western shelf represents worst ecological conditions dominated by the absence of forage fish stocks and the persistence of relatively strong *Mnemiopsis* and *Noctiluca* predation controls. As the jellies and planktivorous fish group were the competitors for feeding on trophic zooplankton, the post-eutrophication state appears to be more strongly controlled by the undesirable jelly-dominated system. On the other hand, the impacts of opportunistic and gelatinous species were less critical in the northeastern and the southern Black Sea, but the northeastern region continued to be depleted by forage fish stocks.

The anchovy spawing stock biomass estimates for 1967–2000 provided by Shlyakhov and Daskalov (2009) and the more recent one for 1990–2014 by STECF (2015) are markedly different (**Figure 3B**). While the stock does nıo exceed 400 ktons in the former estimate, the more recent one provided an increasing trend up to 1,200 ktons during the 1990s, and declined abruptly afterwards below 600 ktons in 2005. However, it is hard to accept the realism of such a drastic increase in the fish stocks during the period of maximum predation impact of *Mnemiopsis* in the ecosystem. Nevertheles, its is interesting to note that its temporal changes follow closely those of SST and CIL temperature depicted earlier in **Figure 2**. Apparently, being a warm water species, cold years are expected to be unfavorable for anchovy growth as indicated by the declining trend of the parental anchovy stocks

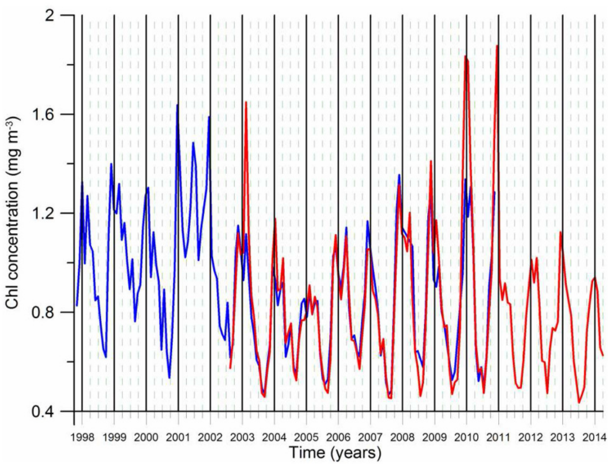

FIGURE 8 | The monthly-mean chlorophyll-a concentration variation of the post-eutrophication phase (1998–2013) averaged for the region 30–41°E longitude and 41–45°N latitude. The data are retrieved from the SeaWiFS (blue) and the MODIS (red) ocean coor sensor.

during the cold years of 1980s and the first half of 2000s contrary to a strong increasing trend during warming years of 1990s. Of course, the climatic pattern is modulated simultaneously to some extent by the non-climatic factors (e.g., fishery over-exploitation, outburst of *Mnemopsis* population).

The Present State of Fishery

At present, the Black Sea is devoid of predatory fish species, and roughly 85% of the total fish catch comprises the low cost anchovy and it is limited mostly to the southeastern region. It represents globally one of the worst case situations in terms of inappropriate management policy causing such a drastic collapse. The fleet overcapacity, mostly the Turkish one, causes to catch more fish than its sustainable level and above the quotas through illegal or unreported catches. The quotas have been and are still enforced under political and social pressures to support short-term fishing prospects instead of the long-term sustainability, as many subsidies in the fisheries sector foster overcapacity and overexploitation of fish stocks. Complexity of pressures introduced by multiple stressors (eutrophication, alien species invasions, natural climatic variations) on the food web functioning further exacerbates the situation. As elaborated by the analysis given above, the distinction of this overfishing/recovery problem is its intimate link to the simultaneous severe degradation of the lower trophic level food web. Therefore, in the Black Sea, the fight for recovery is much more challenging and needs going along with rehabilitation measures of the ecosystem structure. It therefore differs substantially from the overfishing problem of an ecologically undegraded (or much less degraded) system, for which the main target of maintaining sustainable fishery can be achieved by more straightforward management actions.

RESEARCH PRIORITIES AND KNOWLEDGE GAPS

The recent eggs and larvae surveys conducted within the Turkish Exclusive Economical Zone confirmed limitations on our understanding of the post-collapse characteristics of the anchovy stock behavior (Gucu et al., 2017). Generally speaking, fisheries science and biological oceanography pursue in the Black Sea independently from the progress made in understanding lower trophic food web dynamics and transfering knowledge from other disciplines. However, the current Black Sea recovery and restoration problems require building bridges across scientific and management barriers through better science communication between scientists, key stakeholders, and the community by efficient coordination between science, policy, and practice.

The Black Sea scientific community has a lot more to do for achieving a better understanding of the way in which cumulative effects of multiple stressors keep modulating overall ecosystem functioning. In spite of reduction in eutrophication and weakening of jelly and fish predation pressures in the ecosystem, there is no sign of an appreciable ecosystem rehabilitation. One explanation is the irriversibility of the present ecosystem state developed following the regime shift of the early 1990s. There is a major knowledge gap on how and when the current state of ecosystem may settle into an alternative ecologically more desirable equilibrium state. Its assessment on quantitative grounds is of crucial importance in terms of developing management strategies.

Recovery of major fish stocks and management of existing stocks under the pressures by multiple stressors appears to be a challenging task. It requires determining likely recovery paths of the ecosystem under different combinations of pressures, and its understanding demands an extensive scientific research. A part of this general problem concerns an estimation of the energy diverted to the jellies and opportunistic species under different climatic and environmental conditions.

The lack of systematic time series measurements hinders assessing current status of acidification and its vertical structure in the aerobic part of the water column. The current ecosystem models are presently not coupled with the carbonate chemistry to investigate the acidification problem under synergistic effects of climate change and eutrophication. How the Black Sea ecosystem might respond to future changes in climate in combination with other drivers appears to depend on characteristics of other stressors (Niiranen et al., 2013). Preliminary studies have been conducted by Cannaby et al. (2015) but a deeper analysis under different scenarios of stressor combinations (different combinations of fishing and nutrient load management scenarios) are worthwhile to perform.

Recently, there is a growing evidence in the literature that small mesoscale and submesoscale flow features may have critical impacts on the food web structures. This implies integrating small scale physics more accurately by means of fine resolution observations and mass balance food web models that are frequently used as a fishery management tool. Another important research subject is to improve model uncertainties and optimize the trade-offs between complex and simple models. Increasingly complex models provide detailed simulations but require large datasets for model setup/validation and generate outputs which are difficult to synthesize and interpret. In addition, a holistic modeling approach (ecological + socio-economic models) is an enormous undertaken due to insufficient knowledge of the system. On the other hand, simple models due to generalization of processes or coarse spatial/temporal resolutions may fail to capture important ecosystem features. An important criterion for these models is to be able to come up with solutions that do not require complicated and expensive implementation, prohibitive data requirements, and long-term applications.

In general, scientific research was not encouraged by state agencies in the past due to their reluctance for investing onto oceanographic research programs, data sharing and pooling, and it is not clear how much research can be realized under present economical capabilities and priorities of the riparian countries. But, as implied by the present analysis, performing an intensive ecosystem level research is absolutely essential to build up a basis for planning and realization of ecosystem-based adaptive management strategies. Because of the regional differences in ecosystem characteristics, these studies may be partly conducted as the region specific. The current experience also suggests enormous difficulties to be faced along the road. For example, in spite of more advanced research capacity and broader scientific basis, the management strategies developed in the Baltic Sea was found to be not accurate enough to exploit resources and the environment in an adaptive, sustainable manner. One particular difficulty was associated with the non-linearly interacting effects of ocean acidification, eutrophication and climate change (Jutterström et al., 2014).

CONCLUSIONS

The present Black Sea ecosystem undergoes a slow recovery once perturbed and degraded since the 1970s. However, the fishery reveals no sign of recovery after its collapse at the end of 1980s. At present, nearly all commercially important fish stocks have been severely depleted due to decades of unsustainable fishing efforts resulting from excessive fishing capacity and inappropriate fishing practices. The present Black Sea fishery is limited to anchovy and even this economically undesirable, low-income fishery is concentrated only to its southeastern part. The rest of the sea does not support much fish. This is a unique and devastating case among the large marine ecosystems in the world and represents an almost collapsed ecosystem with a size of ~400,000 km^2, not a small bay or coastal ecosystem.

In addition to the inappropriate management measures, the lack of recovery may also be related to the impacts of external pressures on the food web functioning. These pressures impose negative effects on the recovery and may make the system resilient to switch to a new alternative stable (healthy) state. Therefore, the overfishing problem is more than setting quotas and reducing the fleet capacity and demands a holistic approach by considering two-way interactions between higher and lower trophic levels and biogeochemical processes. Clearly, first thing to do is to reduce the fleet capacity to a level that maintains a balance between available fishing effort and resources, to set catch limits for fish stocks in consistent with scientific advice, to ban fisheries for particular stocks and/or regions. However, the management strategy needs to include additionally ecosystem-level planning and ecosystem-based integrated assessments. This approach involves recognizing and addressing interactions among different spatial and temporal scales, within and among ecological and social systems, and among stakeholder groups. It also needs an efficient coordination between science, policy, and practice for addressing key research needs, building interdisciplinary scientific capacity, and synthesizing and communicating scientific knowledge to policy makers, managers, and other stakeholders. Implementation of ecosystem-based management strategy requires operational tools that are developed collaboratively by scientists and managers. For all these efforts, scientific advice is of critical importance and the Black Sea community may benefit from the experience and know-how developed in the Baltic Sea due to their close similarities.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

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REVIEW
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Key Economic Characteristics of Italian Trawl Fisheries and Management Challenges

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Two key measures of economic performance are calculated and analyzed for three important Italian trawl fisheries (Northern Thyrrenian Sea, South of Sicily, Northern Adriatic Sea): the Net Economic Returns (NER), which informs on the economic performance and is considered a proxy of resource rent in fisheries and the Return on Fixed Tangible Assets (ROFTA), which is used as an approximation of the Return on Investment (ROI) and is a key financial and performance indicator for a fisherman in order to take a decision to operate in a fishery. The trend of these indicators over the last decade highlights a poor economic performance that is associated with an overall poor condition of the state of resources. The trend of economic performance indicators is put in relation, on a time-based approach, with the different types of management measures applied over the last decade. We show that trends of fishing effort and economic indicators as well as statistical analysis return a coherent interpretation of the main factors affecting the profitability levels of the selected fleets. The study reveals that management measures impacted negatively on the profitability of the sector in the short run. However, economic indicators inverted the trend in the last 3 years. An increasing biomass trend as well as the improvement in fishing mortality of some few stocks, together with the reduction of input costs could be considered as positive drivers which impacted positively on economic profitability of the fisheries concerned. The study argues that even the technical and fishery management provisions in the Mediterranean Sea may have started to reverse the trend in economic profitability of the analyzed fleets. An additional management effort needs, however, to be developed on an urgent basis in order to ensure the achievement of the management goals defined by the Common Fisheries Policy (CFP).

Keywords: trawl fisheries, economic indicators, management arrangements, challenges, management plans

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INTRODUCTION

The fishery sector plays an important role in the Mediterranean. The officially reported fishing fleet operating in the Mediterranean comprises some 81,600 vessels, with total landings of 787,000 tons (FAO, 2016). The total value of fish landings across the Mediterranean is estimated to be about 3 billion USD; around 300 thousand fishermen are employed on fishing vessels in the Mediterranean and the Black Sea (Mitolidis and Ziegler, 2017).

The marine resources and ecosystems of this region have come under increasing pressure in recent decades, driven by demographic and economic growth as well as by diversification and intensification of marine and maritime activities. The ongoing fishing pressure is determining a general overexploitation status of commercial stocks with more than 90% of the stock assessed out of safe biological limits (Colloca et al., 2017). In addition, environmental factors play an increasing role in disrupting the productivity of stocks and fisheries as recently observed in the North Adriatic where a reduction in nutrient loading (phosphate) during early 1980s seems to have contributed to a major decline in fisheries landings (Fortibuoni et al., 2017).

Deterioration in the status and prolonged overexploitation of some fish stocks are undermining the economic performance of EU Mediterranean fleets (DGMARE, 2017) that decreased in the last decade (STECF, 2015b). The decline in economic profitability was also driven by other factors in combination with the effects of overfishing: poor marketing and market saturation; increased competition with imported products; increasing costs (e.g., fuel costs) and a shortage of local crews (DGMARE, 2017).

Within this context, the sustainable utilization of living marine resources and the implementation of rational management in the Mediterranean are of paramount importance to achieve a long-term sustainability of fisheries. Over the years, various measures have been adopted by the European Commission and the General Fisheries Commission for the Mediterranean (GFCM), with the aim of achieving sustainable levels of fishing pressure and safeguarding habitats. The Common Fisheries Policy [CFP, Regulation (EU) 1380/2013, (EU, 2013)] requires to restore and maintain populations of harvested stocks above levels that can produce the maximum sustainable yield (MSY). Even without identifying specific economic and social objectives, the CFP calls for both economic and social sustainability by specifying that management measures should "contribute to a fair standard of living for those who depend on fishing activities, bearing in mind coastal fisheries and socio-economic aspects" (art. 2 of EU Reg. 1380/2013, EU, 2013). Indeed, environmental and economic sustainability are not contradictory goals; several studies confirm that achieving MSY will result in economic gains because fishing at MSY or lower will lead to higher incomes and lower operational costs (Beddington et al., 2007; Guillen et al., 2016).

In this context, management strategies have been implemented in the Mediterranean with the general aim to ensure biological, environmental, and economical sustainability, even if most of these measures do not adequately specific targets in terms of biomass (B_{MSY}) or fishing mortality (F_{MSY}) at MSY. The assessment of both the biological and economic impacts generated by the management measures included in regulatory framework is a difficult task, also considering the high number of derogations asked by EU Mediterranean Member States in the implementation phase of several measures.

In the present study, we aimed at addressing the effects of prices dynamics (e.g., fuel costs, average prices of landings) and enforced management measures on EU Mediterranean trawl fisheries by focusing on three important Italian fleets (Northern Tyrrhenian Sea, South of Sicily, and Northern Adriatic Sea). To this aim we reviewed in a diachronic way all available economic data and model economic indicators to investigate the main factors that affected the trend in economic profitability of the selected fleets. The relationships between observed pattern of economic indicators with the management measures enforced in the last 10 years were analyzed to evaluate their impacts on the fisheries profitability.

MATERIALS AND METHODS

Area of Study and Selected Fleet Segments

The study was focused on three trawl fleets representing 56% of Italian bottom trawlers and operating in important fishing areas (FAO Geographical Sub Areas: GSA) namely Northern Tyrrhenian Sea (GSA 9), South of Sicily (GSA 16) and Northern Adriatic Sea (GSA 17), (see **Figure 1**).

GSA 9 extends over 42,410 km^2 and includes the Ligurian Sea and the central Tyrrhenian Sea. The fishing fleet operating in the upper and middle Tyrrhenian Sea is marked by a high proportion of small-scale fishing, although trawlers provide the highest levels of actual and economic output. In 2015, around 300 trawlers employing 800 persons on board operated in GSA 9. Almost 50% of total landings are represented by five species: red mullet (*Mullus barbatus*), European hake (*Merluccius merluccius*), horned octopus (*Eledone cirrhosa*), deep-water rose shrimp (*Parapenaeus longirostris*) and spottail mantis squalid (*Squilla mantis*). According to the most recent stocks assessments carried out by GFCM/SAC (2016) and STECF (2015a), European hake and red mullet are exploited unsustainable and only deep-water rose shrimp shows sustainable exploitation rates in recent years.

GSA 16 represents the northern part of the Strait of Sicily. It is considered an area with a high productivity of fish resources, covering about 34,000 km^2. The production structure of the area is characterized by a strong presence of bottom trawling boats that give the sector an industrial connotation. The productive structure engaged in GSA 16 trawl fishery in 2015 consisted of 413 trawlers, 27% of which are bigger than 24 m. Around 1,800 persons worked on board of these vessels. Differently from other areas bottom trawling is targeted mainly to crustaceans, deep-water rose shrimp (*P. longirostris)*, giant red shrimp (*Aristaeomorpha foliacea*) and European hake (*M. merluccius*) representing almost 60% of total landings. All these three species show a general overfishing condition (STECF, 2015a).

GSA 17 covers the entire northern and central Adriatic with a total area of some 92,660 km^2. Most of the sea floor is on the continental shelf and is covered with muddy and sandy sediment of varying granulometry and composition. The trawl fleet operating in GSA 17 consisted, in 2015, of 578 vessels with an on-board employment of about 1,700 units. The main commercial species are spottail mantis shrimp (*S. mantis)*, European hake (*M. merluccius)*, red mullet (*M. barbatus*), common cuttlefish (*Sepia officinalis*), musky octopus (*Eledone moschata*), representing 40% of total production. Red mullet, European hake and the spottail mantis shrimp have been overexploited in recent years (STECF, 2015a).

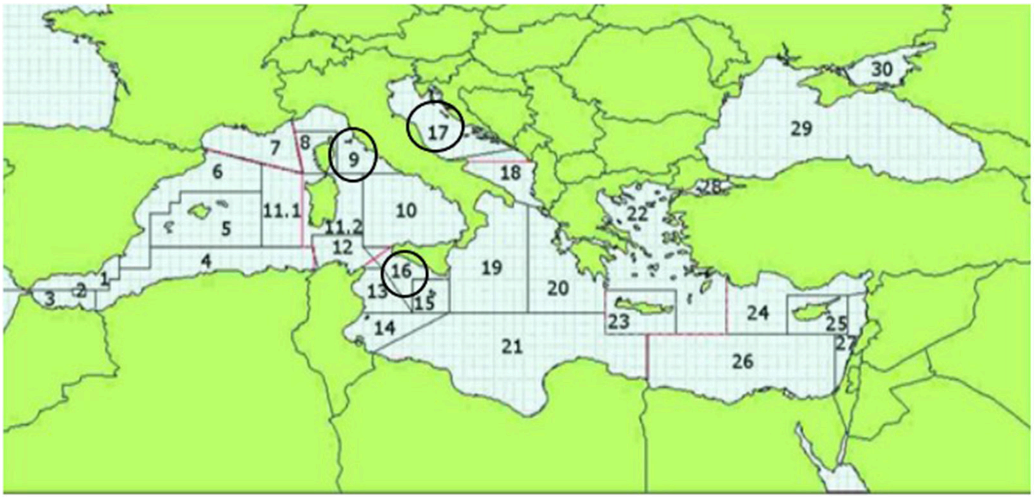

FIGURE 1 | FAO Geographical Sub Areas.

Management Measures

In line with the advice of most international fisheries management bodies, particularly the GFCM, for a long time a management regime based on effort has been considered the most appropriate management strategy for the Mediterranean (Caddy, 2009). The management scheme includes effort control tools (permanent and temporary withdrawal) combined with technical measures, such as closure of areas and seasons, restrictions concerning fishing gears and minimum landing sizes of main commercial species. The main management measures implemented in the selected area are summarized in **Table 1**.

Reg. (CE) 1967/2006 concerning management measures for the sustainable exploitation of fishery resources in the Mediterranean Sea (hereafter referred to as "the MEDREG") introduced several technical measures and promoted "a different approach to fisheries management based on a decentralized decision-making process and on setting up multi-annual management plans both at national and community level" (EC, 2006; Marchal et al., 2016). In the selected GSAs, four national management plans for trawlers were adopted in 2011. The management plans were based on permanent withdrawal of an agreed number of trawlers to decrease the fishing effort and some additional measures (see **Table 1**), as temporary withdrawals and restrictions to trawling of nurseries to improve the exploitation pattern of catch.

In this study, we associated the timing when the different management measures were implemented with the timing when they started to impact on the fishing activities. In particular, we considered the following turning points:

MEDREG:	Implementation of MEDREG. It was approved in 2006 but the innovations with the greatest impact became effective as from 2010.
NMFPs:	Adoption of National Management Fishery Plans (NMFPs), May 2011.
FishBan6m:	Fishing ban within the 6 miles. Since 2012, trawling is prohibited within a distance from the coast of 6 miles or with a depth of <60 m after the seasonal closure in North Adriatic Sea. Before 2012, the same ban applied only within 4 miles. A similar measure was introduced in 2013 through the local management plans in GSA 16, in the area out of Mazara del Vallo and Lampedusa.
EFF b-b p:	EFF buy back program. In 2013, around 13% in GT of the Italian Mediterranean fleet was withdrawn (MRAG, 2013).

These turning points have been introduced in the statistical analysis to assess their eventual impact on the profitability of the selected fishing fleets.

Fisheries Data and Economic Indicators

Time series for the period 2004-2015 on capacity, effort, production, and economic information for the selected fleet segments were obtained from relevant STECF reports and electronic data annex tables (https://stecf.jrc.ec.europa.eu/reports/economic). These datasets were complemented with economic data from the Italian National Program under the European Data Collection Framework (DCR, Reg. CE 1543/00 until 2008 and DCF, Reg. EU 199/08 DCF, thereafter), as well as data included in Mannini and Sabatella (2015). Economic data collected under DCR/DCF include several variables such as income, personnel costs, energy costs, repair and maintenance costs, other operational costs and capital costs (depreciation and opportunity cost of the capital). Definition of variables and methodologies for estimation are prescribed in the DCF through coordination activities carried out by European expert groups (Sabatella, 2016).

A wide range of economic indicators exists for analyzing the economic sustainability of fisheries (Ceriola et al., 2008). Among these indicators, we selected the Net Economic Returns (NER)

TABLE 1 | Management measures for demersal trawlers in GSA9, GSA17, and GSA16 from 2002.

Legislative references		Period of implementation	Management measures	Description
Regulation (EC) No. 2371/2002 on the conservation and sustainable exploitation of fisheries resources under the Common Fisheries Policy (articles 11 to 16, Adjustment of fishing capacity) (EC, 2002)	Council Regulation (EC) No 2792/1999 Financial Instrument for Fisheries Guidance (FIFG)	2002–2006	Adjustment of fishing capacity	Objectives were established in relation to two reference parameters (fleet tonnage and engine power, as of 1 January 2003) and through continuous monitoring of the differential between new entries and exits from the fleet
	Council Regulation (EC) No 1198/2006 European fisheries fund (EFF)	2007–2013	Fleet capacity reduction	Decommissioning Plans have been drawn up in order to quantify the objectives of permanent withdrawal required by the EFF and to activate the measure of temporary withdrawal
Reg. (CE) 1967/2006 concerning management measures for the sustainable (EC, 2006) exploitation of fishery resources in the Mediterranean Sea (MEDREG)	Chapter III MEDREG Fishing Protected Areas Chapter IV MEDREG Restrictions Concerning Fishing Gears Chapter V MEDREG Minimum Sizes of Marine Organisms	Approved in 2006 but the innovations with the greatest impact became effective as from 1 June 2010	Minimum mesh sizes	For towed nets, the net shall be replaced by a square-meshed net of 40 mm at the cod-end or, at the duly justified request of the ship-owner, by a diamond meshed net of 50 mm.
			Minimum distances and depths for the use of fishing gears	The use of towed gears is prohibited within 3 nautical miles of the coast or within the 50 m isobath where that depth is reached at a shorter distance from the coast. In any case, the use of trawl nets is prohibited within 1.5 nautical miles of the coast. In GSA 9, a derogation allows to use towed gears between 0.7 and 1.5 nautical miles of the coast.
			Minimum sizes of marine organisms	A marine organism which is smaller than the minimum size specified in Annex III shall not be caught.
			Restrictions concerning fishing gears	Fishing with trawl nets, above seagrass beds of *Posidonia oceanica* or other marine phanerogams and mäerl beds is prohibited.
	Chapter VII MEDREG Management Plans	May 2011—December 2016 Ministerial Decree 20 May 2011, approval of National management fishery plans (NMFPs) Ministerial Decrees implementing the seasonal closures (one Decree is issued every year)	Seasonal closures	Each year a temporary closure is established for bottom and mid-water pair trawlers. Thirty to forty-five days of seasonal closures is set based on the recruitment season of the most significant target species.
			Other restrictions on fishing activities	Bottom and mid-water trawlers cannot operate on Saturdays, Sundays and during holidays all year round. During the 8 weeks following the seasonal closures trawlers cannot operate on Friday
			Restrictions to Essential Fish Habitat (mainly nurseries)	Biological Protection Zones (BPZ) have been established; in these areas, towed gears are not allowed to fish 2 BPZs in GSA9, 5 BPZs in GSA17, 2 BPZs in GSA16. The ZTBs in the GSA 16 have not been yet implemented.
			Restrictions to trawling areas	Since 2012, trawling is prohibited within a distance from the coast of 6 miles or with a depth of <60 m from July to October in GSA 17 (North Adriatic Sea)
Reg. (EU) No 1380/2013 on the Common Fisheries Policy (EU, 2013)	Article 22 CFP	2016	Action plan for the fleet segments with identified structural overcapacity	5.5% of reduction of fishing capacity for trawlers in 2016

(Continued)

TABLE 1 | Continued

Legislative references		Period of implementation	Management measures	Description
	Article 22, Annex II CFP	1 January 2014 - ongoing	Adjustment and management of fishing capacity	fishing capacity cannot exceed at any time the fishing capacity ceilings set out in Annex II (for Italy 173,506 GT and 1,070,028 kW)
	Article 15 CFP Commission Delegated Regulation (EU) 2017/86 establishing a discard plan for certain demersal fisheries in the Mediterranean Sea	1 January 2017 - ongoing	Landing obligation	All catches of species subject to minimum conservation reference sizes as reported in Annex III of Regulation (EC) No. 1967/2006, must be brought and retained on board fishing vessels, registered, landed and counted against the quotas, if applicable, unless they are used as live bait (EC, 2006)
REC.CM-GFCM/40/2016/4 establishing a multiannual management plan for the fisheries exploiting European hake and deep-water rose shrimp in the Strait of Sicily (GSA 12 to 16)		February 2016 – ongoing *Not yet fully implemented by EU and national legislation*	Technical measures (Fisheries Restricted Areas, temporal closure, list of operating vessels)	Three Fisheries Restricted Areas (FRA) where bottom trawling is prohibited have been established. Buffer areas have been set up around the FRA in order to avoid accidental access to the FRA. Any fishing activity with bottom trawlers in the buffer areas shall ensure their frequency of transmission of vessel monitoring system (VMS) signals.
Ministerial Decree 1 June 2017		From 1 September 2017	Marine Manag. Area in Pomo Pit (GSA 17)	Absolute ban of demersal fisheries in the larger central part of the area Two buffer areas with restricted fisheries regime

and the rate of Return on Investment (ROI) because they are two key measures of economic performance (ABARES, 2016).

NER, also known as Earning Before Interests and Taxes (EBIT), informs on the economic performance and is considered a proxy of resource rent in fisheries. ROI is a financial performance measure and it affects the fisher's decision to operate in a fishery. The definitions of these indicators are as follows:

$$NER = revenues - (explicit\ costs + capital\ costs)$$ [1]

$$ROI = (NER/total\ investment) * 100$$ [2]

NER measures the returns earned from a fishery's operation across a financial year. It is an indicator of the efficiency by evaluating the total costs of inputs (excluding natural resource costs) in comparison to outputs or revenue (STECF, 2015b). The concept and economic interpretation of NER differ from the "gross profit" which is the normal profit after accounting for operating costs, excluding capital costs, giving an indication of the commercial profitability of an industry. This means that negative gross profit is tolerable only for a very short period (depending on the availability to access to credit), while a negative NER for a short period does not imply the financial unsustainability of the fishing activity but it indicates a non-efficient use of resources in a macroeconomic concept. NER has been calculated for the selected fleets for the period 2004-2015. Economic values have been adjusted to 2015 level using the Italian index of inflation rate (ISTAT, 2016).

ROI measures the profitability of a sector in relation to its total assets. The purpose of ROI indicator is to measure, per period, rates of return on money invested in an economic entity to decide whether to undertake an investment. It measures the financial profit at full equity as a percentage of total capital for the average vessel in a fishery. ROI compares the long-term profitability of the fishing fleet segment to other available investments. A value less than zero or smaller than the low-risk long term interest rates available elsewhere, is an indication of long-term economic inefficiency and overcapitalization. The capital invested in the sector should include both tangible and intangible assets. In the fishing sector, vessels, fishing gears, and other equipment can be considered as tangible assets; while intangible assets are generally referred to the fishing rights. When data on intangible assets (fishing rights) is not included in the calculation of this indicator, the name "Return on Fixed Tangible Assets (ROFTA)" is preferred to ROI. As data on intangible assets (e.g., fishing rights, natural resource) are not always available in fisheries, ROFTA is used as an approximation of ROI (STECF, 2012).

Statistical Modeling

A random effect model using the Generalized Least Square (GLS, Green, 2012) estimator was applied to estimate the effects of input and output prices, as well as selected management measures on

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[1] Where:
Revenues = value of landings + other income (income from vessel activities other than fishing)
Explicit costs = all operational costs (such as wages, energy, repair and other variable and non-variable costs)
Capital cost = depreciation + opportunity cost of capital

[2] Where:
Total investment = tangible and intangible asset value

NER. Annual data 2004-2015 have been organized by GSA, NER, Revenues, Costs, Fuel prices and average landing prices.

An "indirect NER function" was estimated assuming as dependent variable the ratio between revenues and total costs and independent variables the average price of landing and the average cost of the fuel. All the variables are in logarithms. In the loglinear equation, the coefficient are elasticities. β_x measure the percentage change in NER associated with a one percent change in each explanatory variable.

$$\log \mathrm{NER}_t = \beta_1 \log(\text{price of landings})_t + \beta_2 \log(\text{fuel cost})_t + \beta_3 \text{ dummy} + \text{cons}_t$$

The management measures identified as "turning points" were introduced as dummy variables. We considered four dummies, each one for a single measure. They have been introduced in the model considering the year from when they started to likely impact the fishing sector (**Table 2**). When a new measure is introduced, its impact is added to the impact of measures already in place.

RESULTS

Over the period 2004-2015, in line with the fishing effort adjustment process stimulated by public funding, negative changes have been recorded for all physical capacity indicators. The trawl fleets decreased in number by 36% in GSA 17, 15% in GSA 09 and 20% in GSA 16. Gross Tonnage (GT) showed a similar decrease (**Figure 2**). The reduction in fleet capacity highly affected the activity levels. Days at sea in GSA 17 decreased by more than 50% from 2004 to 2015 (**Figure 3**). As a consequence of the adjustment of the effort levels, the volume of fish production of the trawler fleets in the selected GSAs, decreased in the last decade by 48% in GSA 17, 31% in GSA 16 and 8% in GSA 9.

Regarding the economic indicators, trawlers in the three selected GSAs showed a decreasing trend of ROFTA until 2012-2013 followed by an increase in the last 2–3 years, with the lowest performance observed in GSA 16 (**Figure 4**). The NER trends across the fisheries showed a similar pattern for the three fleets, with a constant decrease in the period analyzed (**Figure 5**). All the fisheries have experienced a negative NER at some point since 2008 achieving a minimum in 2012-2013. An increase in NER was observed in the last 3 years of the period under analysis.

The trend in NER was a likely effect of a combination of various factors. Five different estimates of the Indirect NER function were produced (**Table 3**) to statistically assess the impact on profitability of input costs (namely fuel cost), average landing prices and the introduction of management measures. The results, despite the limited number of observations, highlighted that the variable related to landing prices is not significant, meaning that trend in real landing prices did not explain the trend in NER, while the fuel price is always significant with the (expected) negative sign (**Table 3**).

TABLE 2 | Selected management instruments introduced in the statistical modeling.

Management instruments/measures	Dummy code	Starting year
MEDREG	du10	2010
MEDREG + NMFPs	du11	2011
MEDREG + NMFPs + FishBan6m	du12	2012
MEDREG + NMFPs + FishBan6m+EFF b-b p	du13	2013

The impact on profitability of the introduction of management measures has also been simulated in the model through the introduction of four dummies. The management measures considered in the model are those with the supposed higher impact on fishing activities. They are reported in **Figure 5** together with the trend of NER from 2004 to 2015, adjusted to 2015 level. The results of the models confirm that all dummies are significant with a probability lower than 10% and negative as well. In the fifth output of the model, the logarithm of fuel cost and the dummy assuming 0 for the years 2004 and 2012 and 1 for the year 2013 report *p*(value) lower than 0.01. These results seem to confirm that the introduction of management measures impacted on profitability. Indeed, the parameters of the statistical analysis are negative, confirming that in the short run the economic impact of the measures was negative in terms of profitability because they imposed additional costs to adapt fisheries to the new rules.

In synthesis, over the last decade, the trawling fleets in GSA 9, GSA 16, and GSA 17 followed similar trends, summarized in a reduction of the production structure, decline in capacity and activity, and decrease in physical and economic returns. However, economic indicators (NER and ROFTA) inverted the trend in the last 3 years (2013-2015). These improvements are linked to reductions in fishing capacity associated with fishery level cost decreases. Stock variation and management changes are additional factors that could eventually have positively impacted on economic indicators. Considering the availability of data and the short time series, it is not possible to assess if the inverted trend of the last 3 years is a structural one, or just a fluctuation due to market conditions and oscillation of input prices.

DISCUSSION

We showed that the nominal fishing effort has decreased remarkably in the last 10 years. This reduction was accompanied by a structural resizing of the productive structure even in terms of total landings. The capacity reduction was stimulated by public funding but also by a voluntary departure from the sector due to the general obsolescence of the fishing fleets and to economic factors, such us the low physical productivity and the increasing operating costs. Despite the reduction in the number of vessels and gross tonnage of the fleet, the results of stock assessments demonstrate that stocks are still largely overfished and/or in a bad state (European Commission, 2016). However, the ratio F/FMSY for some important target stocks of demersal fleets like red mullet and giant red shrimp has significantly declined over time, even if the value is still above 1 (2.5 and 1.1, for red mullet and giant red shrimp, respectively), as shown by Cardinale and Scarcella (2017).

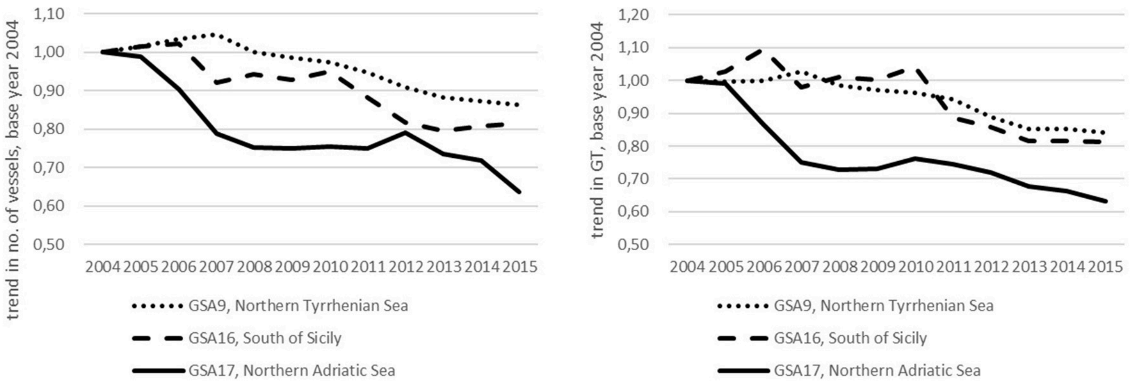

FIGURE 2 | Trend in capacity of the trawling fleet in selected GSAs.

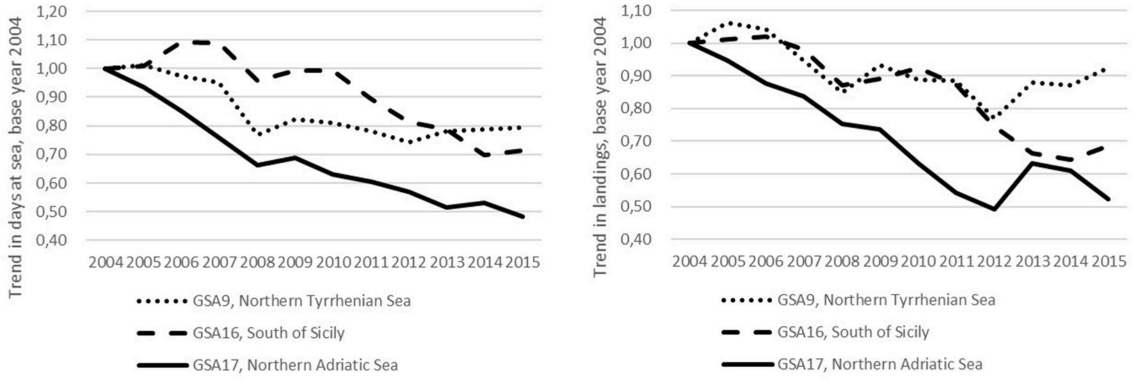

FIGURE 3 | Trend in activity and production of the trawling fleets in selected GSAs.

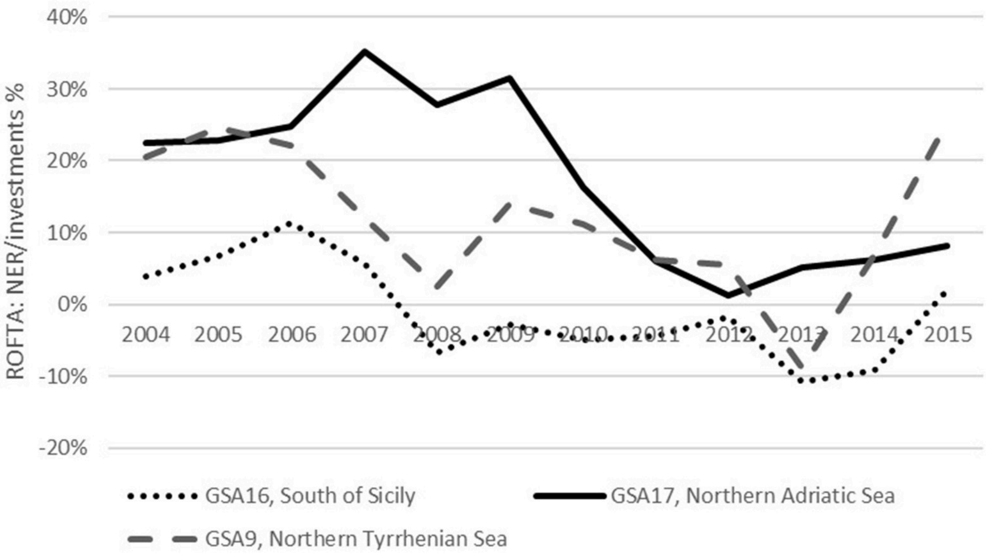

FIGURE 4 | Rate of return for selected European fishing segments operating in the Mediterranean.

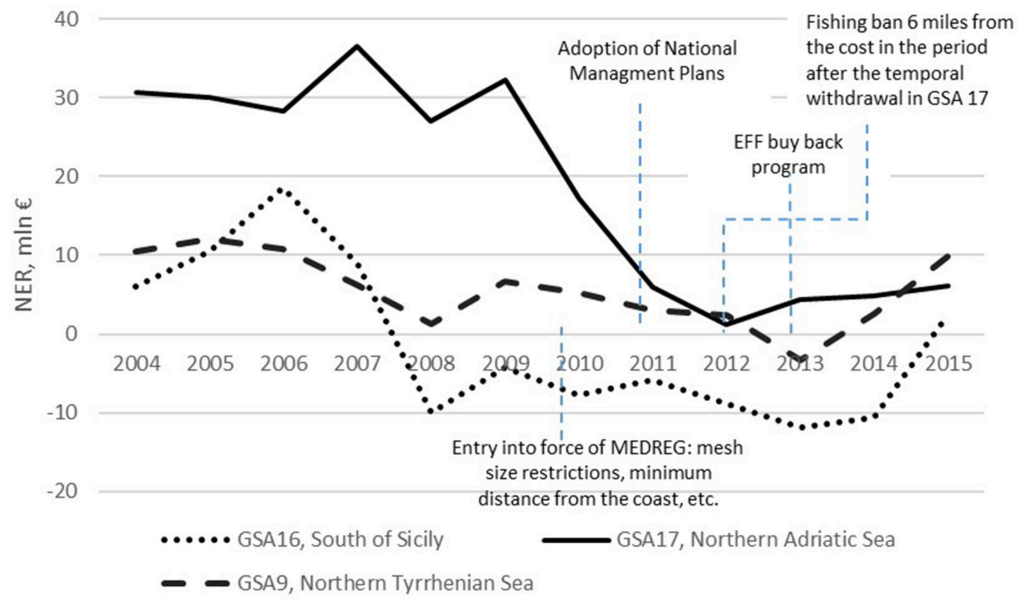

FIGURE 5 | Net Economic Return for selected European fishing segments operating in the Mediterranean.

TABLE 3 | The Indirect NER function.

Variable |	I	II	III	IV	V
llandprice |	0.0209				
lfuelprice |	−0.0911	−0.0837*	−0.0834*	−0.1119**	−0.1367***
du10|	−0.0532*	−0.0564***			
du11|			−0.0556***		
du12|				−0.0486***	
du13|					−0.0549***
constant |	0.0080	0.0544	0.0522	0.0323	0.0187
N |	36	36	36	36	36
sigma |	0.0470	0.0965	0.0967	0.0974	0.0969
r2_o |	0.2485	0.2461	0.2384	0.2198	0.2347

The Econometric Results. Years 2004-2015. legend: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Data analysis also presented the critical economic status of the trawling fleets. The negative trend in the NER highlighted the inefficiency of the sectors that is not able to cover the total costs of inputs (excluding natural resource costs) with the revenues obtained by output values. Even the profitability of the sector in relation to its total assets, presented in terms of ROFTA, showed very low if not negative values, thus indicating a situation of long-term economic inefficiency and overcapitalization.

We showed that analysis of trends (effort, production, and economic indicators) and statistical analysis return a coherent interpretation of the main factors affecting the profitability levels. Input prices (and in particular fuel price) in the model were significant and negative, while average landing prices were not explaining the trend in NER. The results of the analysis reinforced the expectation that management measures impacted negatively on the profitability of the sector in the short run. Indeed, once a measure is introduced, the sector should adapt the fishing modalities to the new rules and this process requires new investments and/or increased costs. However, in the medium to long-term period, the introduction of management measures, if effective and if well implemented, should lead to an improvement in the overall state of resources. This fact, together with the overcoming of the adaptive period, should increase the profitability of the concerned fleet. Actually, the data reported in this study, showed a trend change of the economic indicators (NER and ROFTA) in the last 3 years which started to increase. An increasing biomass trend of red mullet and striped red mullet in GSA 15-16 as well as the improvement in fishing mortality level of deep sea pink shrimp in GSA 9 (STECF, 2015a) could be considered as positive drivers which impacted positively on economic profitability of the fisheries concerned. Even the technical and fishery management provisions in the Mediterranean Sea, especially those managed through national management plans, could be considered as drivers producing positive effects in the long term. However, it has to be noticed that the evaluation of the impact of all these drivers is not sufficiently robust from a statistical view because available time series are still too short and because the management measures introduced by the CFP are not yet fully implemented.

The present scenario of EU Mediterranean fisheries is driven by the political concerns with respects to the achievement of the CFP goals. Considering that the exploitation of Mediterranean shared stocks implies a multiple management levels, where the management of resources is outside the responsibility of the individual states, GFCM and European Commission are undertaken several common actions to enforce a rational management and best utilization of living marine resources. GFCM recently implemented the multiannual management plan (MAP) for the demersal fisheries exploiting hake and deep-water rose shrimp in the Strait of Sicily (GSAs 12-16). This MAP represented a clear attempt in the development of a science-based management (Vielmini et al., 2017).

All these recent actions will impact on the biological aspects of the demersal resources as well as on the economic viability of the concerned fisheries. It is premature to forecast the potential impact of these new measures still under implementation. Economic theory suggests that the introduction of new management measures leads to economic losses in the short terms because fisheries need time to adapt to regulation adjustments (Sutinen and Peder, 1985). As shown before, the profitability of the selected trawling fleets is improving, but it is not certain that this improvement is robust enough to internalize the possible shocks coming from the introduction of the new proposed management measures. However, new and more effective management instruments, like Long Term Management Plans, updated National Management Plans based on MSY target and Harvest Control Rules, are needed to face the critical state of Mediterranean resources and ensure a long term economic sustainability of fisheries.

AUTHOR CONTRIBUTIONS

ES: substantial contributions to the conception or design of the work; the acquisition, analysis, and interpretation of data for the work; and drafting the work; final approval of the version to be published; and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. FC: substantial contributions; revising it critically for important intellectual content; and final approval of the version to be published. GC: data analysis and statistical modeling and final approval of the version to be published. FF, MG, LM, and RS: substantial contributions; revising it critically for important intellectual content; and final approval of the version to be published.

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OPINION
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Fisheries Management in the Black Sea—Pros and Cons

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INTRODUCTION

About 85% of the Mediterranean and Black Sea stocks assessed are fished at biologically unsustainable levels (FAO, 2016). The experience of EU fisheries management is unique in its scope and ambition, in that it represents the only example of reconciling the concerns of a variety of coastal countries and eco-regions with diverse, if not divergent, interests into a Common Fisheries Policy, the CFP. The last revision, after adoption and several other revisions of the CFP is referred to as the 2013 CFP throughout the document. It is notable that experiences drawn from other countries' fisheries management have been considered to shape the 2013 CFP and these will likely be accounted for in reviewing future performance (Marchal et al., 2016).

The EC and GFCM are promoting a regional approach to fisheries management in the Black Sea. GFCM (2015) has adopted measures to prevent, deter and eliminate illegal, unreported and unregulated fishing in turbot fisheries in the Black Sea as well as management measures for dogfish. Both sets of measures entered into force were reinforced with additional management measures aiming to further protect the stocks in danger (GFCM, 2016). Yet the regulated stocks in EU waters represents very low percent from the total catch in Black Sea (STECF, 2015; FAO, 2016). For example, sprat catches in EU waters were estimated for 2012–2014 between 4 and 14% and 4.6–7% for EU share of turbot catches. This opinion aims to underline the efforts toward fishery management improvement in the Black Sea in the last years but also to highlight the existing gaps and challenges in sustainable management of marine living resources in the region.

BACKGROUND

Improvements of Fisheries Management

The CFP aims to ensure that fishing and aquaculture are environmentally, economically, and socially sustainable and that they provide a source of healthy food for EU citizens. Its goal is to foster a dynamic fishing industry and ensure a fair standard of living for fishing communities. The current policy stipulates that between 2015 and 2020 catch limits should be set that are sustainable and maintain fish stocks in the long term. The EU and GFCM is showing increasing concerns about Mediterranean and Black Sea stocks, and the Commissions have in several occasions expressed the view that the recovery of Mediterranean and Black Sea stocks should now be regarded with the highest priority (EC, 2015). Following the 2013 CFP Reform, the gradual establishment of MSY as a management target for all fish stocks (including data limited stocks) may potentially render EU TAC decision-making increasingly consistent with scientific advice. Since the inception of the 2013 CFP, the EU has strengthened its management objectives (gradual establishment of MSY to all fish stocks) and conservation measures (gradual implementation of discard limitations), raising better prospects for the future sustainability of its fisheries. Another increasingly important aim is to reduce untargeted catches and wasteful practices to the minimum or avoid them altogether, through the gradual introduction of a landing obligation. Finally, the new CFP has overhauled its rules and management structure, with regionalization and more extensive stakeholder consultation (COM, 2015). In recent years, enormous strides have been made in improving the knowledge and conservation of the region's living marine resources. Management plans are increasingly advocated as an essential tool for fisheries management (FAO, 1996, 2003). They are formal arrangements, between a fishery management authority and interested parties. Management plans specify the agreed objectives for the fishery, the rules and regulations to be applied and other information that may be relevant to fisheries management. Plans can be developed at the local, national and regional level, depending on the jurisdiction of the management authority and the characteristics of the fishery being managed. This opinion text describes recent efforts by the GFCM to apply plans aimed at managing fisheries in the Mediterranean and the Black Sea (FAO, 2016). Work has been under way to develop multiannual management plans for the Black Sea, particularly with regard to turbot fisheries (GFCM, 2014). It was concluded that due to the importance of anchovy, both from a socio-economic point of view and as a key element of the Black Sea ecosystem, and considering its wide distribution and migration patterns as well as the implication, at different levels, for anchovy fisheries in all riparian countries, a GFCM sub regional multiannual management plan should be implemented (GFCM, 2015).

Landing Obligation

With introduction of the landing obligation, the fishing opportunities proposed shall reflect the change from amount landed to amount caught. This is done on the basis of the received scientific advice for the fish stocks in fisheries as referred to in Article 15(1) of Regulation (EU) No 1380/2013. Landing obligation is in force for Black Sea EU countries. For the non EU countries in Black Sea, with total catch more than 80%, for the time being this obligation is not applicable.

Stock Assessments

The conclusions of the third SGSABS meeting reported the status of the Black Sea turbot (*Psetta maxima*) population as both "overexploited" and "in overexploitation." Similarly, the Black Sea anchovy (*Engraulis encrasicolus ponticus*), the Black Sea horse mackerel (*Trachurus mediterraneus ponticus*), the red mullet (*Mullus barbatus*) and the whiting (*Merlangius merlangus*) populations were found to be "in overexploitation." Instead, the piked dogfish (*Squalus acanthias*) population was considered to be "depleted" at the Black Sea scale. In contrast, the Black Sea stock of sprat (*Sprattus sprattus*) was deemed to be sustainably exploited (**Table 1**). The SGSABS advised implementing a recovery plan for turbot and piked dogfish as well as the reduction of fishing mortality for all other stocks with the exception of sprat, for which the advice was not to increase fishing mortality (EC, 2016; GFCM, 2016).

DISCUSSION

Experience with fisheries management worldwide shows that in order to successfully manage the renewable resources of a marine area, compliance of all parties harvesting common resources to a common framework and their agreement on common objectives are both required. The parties should agree on compatible, effective and cost-effective regulations, on the allocation of resources, and on details of implementation of a common fisheries management regime outside territorial waters. These details should be spelled out explicitly in a management plan, which should be upgraded at intervals of 5–10 years. These activities should be reported on following an uninterrupted annual cycle of meetings between the parties concerned, including permanent working parties of national experts, panels on special issues, and commissions made up of accredited government representatives (Caddy, 1999). Some targeted species, such as shellfish, may be relatively static and for management purposes considered to be fully resident in national waters. However the major capture fisheries in the Black Sea migrate within the Black Sea, and are shared with other Black Sea stakeholders. The difficulty of managing fisheries is particularly reflected in the targets assigned to conservation objectives and how management actions are taken to meet these objectives in the short-medium term through to the long term. However, it is typical of political systems that the short-term view is prioritized over the long term (Holden, 1994). Proper management of shared stocks must involve negotiation with stakeholders throughout the range of the species. International agreements and national initiatives may force countries to prepare common fisheries management plans in near future. So, every country should be ready for such actions (Duzgunes and Erdogan, 2008). For a number of reasons which will be alluded to in this text, the Black Sea fisheries community has not been successful in implementing such cooperative activities under all of the above headings, or in "closing the circle" by putting together a working management cycle (Caddy, 1999). The GFCM focused on work toward the adoption of specific recommendations to revert the negative situation of fisheries in the region. However, the information on the status of Black Sea stocks is sparse, with few stocks being regularly assessed and with short time series for these assessments. There are still important uncertainties in the different stock assessments (e.g., estimation of total catches which also includes discards and IUU fishing activity, problems with the coverage of fisheries independent surveys, etc.). Furthermore, the Black Sea is one of the world's most isolated seas from the major oceans and it is the largest anoxic body of water on the planet. This sea is under heavy anthropogenic stress and its marine living resources need protection. Considering the particular characteristics of this sea and the specific challenges it faces in developing management advice, an ecosystem-based management approach that acknowledges the peculiarities of this sea is called for (GFCM, 2016). The level of exploitation varies in the years, as the fishing effort (Van Hoof, 2010) and fishing mortality have been changed during different periods with regards the changes in ecosystem and economic reasons, mainly. As regards the important key species in the Black Sea ecosystem, the measures for sustainable utilization must include wider ecosystem considerations. In this view, measures that advice incorporation of ecosystem approach and rules and guidelines provided by "precautionary approach" (FAO, 1996)

TABLE 1 | Species, data type used for stock assessments, time series, methodology used, stock status, and scientific advice for 7 fish species in Black Sea (GFCM, 2016).

GSA	Species	Data type	Time series	Methodology used	Stock status	F_{curr}/F_{lim}	B_{curr}/B_{lim}	Advice
29	Turbot (*Psetta maxima*)	Total landings; catch-at-age; weight-at-age; natural mortality; maturity ogive; tunning indices	1950–2014	SAM	Overexploited and in overexploitation	5.38	0.29	Implement a recovery plan
29	Anchovy (*E.encrasicolus*)	Total landings; catch-at-age; weight-at-age; natural mortality; maturity ogive; tunning indices (Turkish CPUE)	1988–2014	XSA	In overexploitation	1.33	...	Reduce fishing mortality
29	Picked dogfish (*Squalus acanthias*)	Catch-at-age; weight-at-age; maturity ogive; tunning indices (Romanian CPUE)	1989–2014	XSA	Depleted	3	...	Implement a recovery plan
29	Sprat (*Sprattis sprattus*)	Catch-at-age; weight-at-age; maturity ogive; tunning indices (Turkey and Ukraine CPUE and pelagic surveys from Romania and Bulgaria)	1995–2014	ICA	Sustainably exploited	0.8	...	Do not increase fishing mortality
29	Horse mackerel (*Tr. mediterraneus*)	Total landings; catch-at-age; weight-at-age; natural mortality; maturity ogive; tunning indices (Turkish CPUE)	2005–2014	XSA	In overexploitation	1.96	...	Reduce fishing mortality
29	Red mullet (*Mullus barbatus*)	Catch-at-age; weight-at-age; natural mortality; maturity ogive; tunning indices (Turkish CPUE)	1990–2014	XSA	In overexploitation	1.67	...	Reduce fishing mortality

have to be taken into account in proper management of the key fish populations (Raykov and Zlateva, 2015).

The term "management" usually is interpreted as series of regulatory measures introduced in the fishery practice with no doubt, positive influence on the general condition of marine living resources. On the other hand, similar restrictions could not lead conceptually to the "management policy" if they are not systemized with clearly formulated aims and prerogatives. In the presence of introduced "closed area," "closed season," "minimum mesh size," and other regulations, altogether all of these measures could not serve as restrictions over the yield capacity, i.e., could not influence the fishing effort. The main priority in such a conception is a precautionary approach and responsible fishery practice in force. It could "work" properly with quota principle implementation, together with more effective system control. It is hard for any single country to follow these regulations and it is harder for all Black Sea countries to do so, because they are exploiting resources from shared fish stocks. In order to have an effective management on these stocks, joint stock assessments and co-operated fisheries management plans are needed. On this basis, the allocation of the catches for the separate Black Sea country could be established. Hence, it could be assumed that management of the marine living resources shall be fulfilled in its incomplete form, under the national jurisdiction prescript, as they are. The future of fisheries management in Black Sea is intrinsically linked with the setting of cross-sectoral "Maritime Policy" and "Marine Strategy Framework Directive" (EC, 2008) which deal with the cumulative impact of human activities. Implementation of management procedure involves the practical interpretation of objectives and procedures, and implementation of instructions for compliance, fishery monitoring and enforcement. The public and industry are more inclined to support measures upon which they have been consulted, so public participation at the implementation phase is critical. Public advertising of issues may help in this regard. Peer review of assessments and transparency in the process prevent errors (Pilling et al., 2008). In the Black Sea region the ecosystem approach has not been systematically applied in management, neither it has been previously recognized as a needful and inevitable framework to sustain healthy environment. The scientific message of complexity of ecosystems should reach the decision makers in a way raising their awareness on the necessity to manage the ecosystems in their integrity of health, services and goods. There is an increasing need for adoption of the ecosystem approach to exploitation of marine natural resources to promote ecological, environmental, economic, and social sustainability and preserve biodiversity in the Black Sea region.

CONCLUDING REMARKS

The lack of common fisheries management and management plans, overexploitation and unknown use of the resources, lack of bio-economic analyses, significant loss of revenue and unsustainable development are among most serious problems facing Black Sea fisheries.

As regards Black Sea, it is more properly to put the accent on the separate regulations of the fishery, instead of its integral management. These regulations concern in very small extension the shared fish stocks, which are exploited without sufficient control. The future of fisheries management in Black Sea is intrinsically linked with the setting of cross-sectoral Maritime Policy and Marine Strategy Framework Directive which deal with the cumulative impact of human activities. Major efforts for multilateral cooperation among the riparian countries will be needed in order to improve the governance of the shared and migratory stocks in long term.

AUTHOR CONTRIBUTIONS

VR and ED: Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; Drafting the work or revising it critically for important intellectual content; Final approval of the version to be published; Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Understanding the Impact of Environmental Variability on Anchovy Overwintering Migration in the Black Sea and its Implications for the Fishing Industry

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Black Sea anchovy (*Engraulis encrasicolus*) undertake extensive overwintering migrations every fall from nursery grounds to warmer overwintering areas located on the south-eastern coast of the Black Sea. During migration and particularly upon arrival at the Anatolian coast, they support an important fishery and valuable source of income for the regional community. Black Sea anchovy have undergone significant stock fluctuations partly related to climatic conditions; for example, migrating anchovy schools arrived late or failed to arrive at the Anatolian coast when fall temperatures increased. It is therefore of importance to understand the conditions required for successful overwintering migration and explore different migration routes. This study invokes a Lagrangian modeling approach applied to satellite derived circulation and temperature data as a first attempt to model anchovy migration dynamics in the Black Sea. This modeling approach takes the influence of the physical environment into account, while the quality of overwintering grounds, adaptive, schooling, and homing behavior is neglected. The model is used to investigate the possible influence of interannual and seasonal variability of temperature and surface currents, as well as the influence of migration behavior on the success of anchovy overwintering migration for both the Black Sea and Azov Sea anchovy. The results of the present work show the possibility that overwintering anchovy fished along the Turkish Eastern Anatolian coast may not exclusively originate from the northwestern shelf, but mainly from the eastern Black Sea basin. Migration pathways are identified for both Black Sea and Azov Sea anchovy, which are of importance for the national fisheries efforts of riparian countries. The modeling results are in agreement with general patterns of anchovy migration given in the literature indicating that the physical environment may be a major factor in shaping general migration patterns. Simulation results are used to hypothesize about alternatives to previously determined migration routes and provide potential reasons that explain the inability of the Bulgarian anchovy fishery to recover. Results show that the intensity and timing of autumnal cooling, coupled with current strength, can be of significant importance in determining annual and seasonal variability of migration success. Considering the need for fisheries management to account for the variability in fishable overwintering anchovy stocks a modeling approach as developed in the current study may provide such a tool.

Keywords: Black Sea, anchovy (*Engraulis encrasicolus*), overwintering migration, climate variability, Common Fisheries Policy

INTRODUCTION

The key to estimating the available species in an ecosystem requires an understanding of their geographical distribution (Harte, 2002). Movement can affect fish populations through changes in population density, modifying interspecific interactions or through genetic reorganizations (Turchin and Omland, 1999). In fisheries assessment and management, the patterns of fish movement can be used to explain stock fluctuations (Pelletier and Parma, 1994). The way that marine organisms disperse depends on the species, species behavior, and currents (Marinone et al., 2008). Considering the long-distance migration that anchovy in the Black Sea undergo every year, studying movement of populations can provide valuable insights for fisheries science (Goodwin et al., 2006). Therefore, simulation of movement of individual particles in a dynamic environment is an important tool for investigating ecological processes in the marine environment (Heath and Gallego, 1998; Miller et al., 1998; Hare et al., 1999).

Models are very useful tools for understanding and simulating fish movement under changing environmental conditions (Goodwin et al., 2006). However, modeling the movement of fish is challenging as the mechanisms that cause the movement are often not well-known (Watkins and Rose, 2013) and data is scarce (Haas et al., 2004; Roth et al., 2008). Modeling studies have regularly reported close relationships between small pelagics abundance and distribution patterns and sea surface temperature distributions, i.e., in herring in the Barents Sea (Gjøsæter, 1998; Gjøsæter et al., 1998; Huse et al., 2010), capelin in the Barents Sea (Dommasnes and Røttingen, 1984; Ozhigin and Luka, 1985), sardine in the Pacific (west) coast of the USA and Canada and the seas around Japan (Tameishi, 1996; Huse and Ellingsen, 2008; Zwolinski et al., 2011, 2012) and mackerel in the Norwegian Sea (Iversen, 2002). Modeling results also point out that, changes in the physical environment fish are exposed to may eventually alter migration pathways (Wang et al., 2013).

Anchovy migration in the Black Sea is mainly driven by ambient temperature (Chashchin and Akselev, 1990; Panov and Chashchin, 1990; Panov and Spiridonova, 1998; Berdnikov et al., 1999; Shulman, 2002; Shulman et al., 2008). With the approach of cold temperatures, anchovy adults and juveniles aggregate to form dense schools and start wintering migration toward warmer waters located in the southern Black Sea. The upper temperature thresholds for Black Sea anchovy to start forming schools and begin migration vary. Furthermore, estimates of the temperature threshold at which anchovy start migrating differ ranging from 10.5–13.5°C for juveniles and 11.5–15.0°C for adults (Shulman et al., 2008), minimum of 12°C (Chashchin and Akselev, 1990) or 14°C (Panov and Spiridonova, 1998), or between 12 and 14°C (Panov and Chashchin, 1990). Chashchin et al. (2015) suggest adult Black Sea anchovy start to form migrating schools when the water temperature drops below 16–18°C. It has also been found that the adult anchovy first start migration, and later when the temperature drops further, the juveniles start migration (Gucu et al., 2017). In addition, an internal stimulus driving migration is thought to be the body fat content (Shulman, 2002).

The strong variability in anchovy catches in the Black Sea indicates strong spatial and temporal variability in anchovy biomass. As anchovy is a fast-growing and short-lived species, the influence of environmental drivers may regulate survival rate of the early life stages (Guraslan et al., 2014; Gucu et al., 2016). Of these factors, eutrophication, climate variability (Oguz et al., 2008a,b) and the invasion of an alien ctenophore (*Mnemiopsis leidyi*) have been stated to be of crucial influence.

Two anchovy subspecies are found in the Black Sea, the Black Sea anchovy (*Engraulis encrasicolus ponticus*) and Azov anchovy (*E. encrasicolus maeticus*) (Nikolsky, 2013). Azov Sea anchovy spawning grounds are located in the Azov Sea (**Figure 1**; Chashchin et al., 2015). Black Sea anchovy eggs and larvae have been found in much of the Black Sea, but based on extensive annual surveys of the Soviet Union from the 1970's to early 1990's of the entire northern part of the Black Sea it was concluded that the main spawning ground of Black Sea anchoy is located on the northwestern shelf, rather than the northeastern regions (Ivanov and Beverton, 1985; Chashchin, 1996; Lisovenko and Andrianov, 1996; Chashchin et al., 2015). Unfortunately, this data set does not continue past the solution of the Soviet Union. Later, international studies covering the entire Black Sea in the 1991 and 1992 spawning seasons revealed that in 1992 most anchovy eggs were found in the southern Black Sea, with highest egg densities (1,167 ind m^{-2}) found in the Samsun region and highest larvae densities in the southwestern Black Sea (up to 55 ind. m^{-2}) (Niermann et al., 1994). This pattern of egg and larvae distribution was further confirmed by later surveys along the southern Black Sea coast in 1993 and 1996 (Kideys et al., 1999). Results from a recent ichthyoplankton survey in the southern Black Sea in 2013 revealed egg densities (6–3,051 ind. m^{-2}) and larvae densities (3–359 ind. m^{-2}) to be considerably higher than in previous studies (Gucu et al., 2016). Unfortunately, these surveys were not conducted continuously and over longer time scales, however they suggest anchovy spawning is not restricted to the northwestern shelf but occurs over much of the Black Sea with more or less success.

Adult anchovy densities along the entire southern coast during fall and winter have been determined to be variable during the years 2011–2014, measured as between 3 and 900

Nasc m^2 nmi^2 (Nautical Acoustic Scattering Coefficient) with the highest overwintering densities of 244–949 Nasc m^2 nmi^2 in the southwestern coastal waters in fall 2014 and hotspots of high anchovy densities far offshore waters of the southeastern coast (Gucu et al., 2017). Gucu et al. (2016) hypothesize that there is a southern stock of anchovy that reproduces in the area and is non-migrating.

The overwintering grounds of Black Sea anchovy are located along the southeastern Black Sea coast (**Figure 1**) as recorded by Chashchin (1996) and reconfirmed with recent, multi-year acoustic and landing surveys (Gucu et al., 2017). To reach these overwintering grounds, anchovy must migrate long distances across the Black Sea from the northern shelf spawning and nursery grounds. Black Sea anchovy overwintering migration takes place after the onset of autumnal cooling either at the beginning of October (Ivanov and Beverton, 1985; Lisovenko and Andrianov, 1996; Shulman, 2002) or by mid-November (Chashchin, 1996). Migrating Black Sea anchovy leaving the spawning grounds in the northwestern shelf have been defined to move south along the Romanian and Bulgarian coasts following the rim current eastward along the southwestern Black Sea coast (Ivanov and Beverton, 1985; Chashchin, 1996) and/or move toward the west coast of Crimea and then southwards to the Anatolian coast midway between the Eastern and Western Basin (**Figure 1**).

Likewise, Azov anchovy leave their spawning and nursery grounds in the Sea of Azov and migrate to the Black Sea overwintering grounds (Chashchin, 1996). They follow the Crimean coast migrating across its central basin midway between western and eastern gyres or migrate along the Caucasian coast (**Figure 1**) to overwinter there or they may rarely migrate along the Georgian coast even reaching the Turkish border (Chashchin, 1996 and references therein). Azov anchovy are mainly fished by the Ukrainian, Russian and Georgian fishing fleets, while Black Sea anchovy are fished almost exclusively by the Turkish fishing fleet.

This paper aims to explore the influence of climatic variability in the form of temperature variations and changes in geostrophic surface currents on anchovy distribution in the Black Sea, particularly looking at how this variability affects the migration pathways and success of anchovy moving toward the south-eastern coast where they are fished in the late fall and winter. This is achieved by including adult anchovy swimming behavior and the processes of decision-making into an existing Lagrangian Individual Based Model (Fach, 2014) to investigate possible anchovy overwintering migration routes from different nursery grounds to the overwintering grounds located along the south-eastern coast of the Black Sea in three climatically divergent years (2001–2003). This study represents a first attempt at modeling anchovy migration behavior in the Black Sea and the model results agree well with available data on migration pathways and anchovy distribution during the overwinter season from the literature, but should be validated with detailed survey data on anchovy distribution during migration when it becomes available.

The goal of this research is to understand the different factors influencing successful anchovy migration as well as to determine from which regions in the Black Sea anchovy can successfully migrate. The information gained on the variability of migration success between years and seasons due to the intensity and timing of cooling in fall, as well as the strength of currents, is of significant importance when establishing any fisheries management practices. Fisheries management needs to account for changes in the physical environment when targeting fish stocks (Hofmann and Powell, 1998; Xu et al., 2013; Constable et al., 2014; Checkley et al., 2017).

An Overview of the Black Sea Anchovy Fishery Characteristics

In recent years, the Black Sea fishery was dominated mainly by small pelagics, such as anchovy and sprat (STECF, 2015). Applying a Common Fisheries Policy (CFP) to the Black Sea is a challenging endeavor due to the fact that of the six riparian countries, only two are members of the EU (Romania, Bulgaria) with large legal, economic, political, and institutional differences across the basin and diverse fisheries interests and capacities. Despite attempts to improve fisheries management, there is a lack of effective regional cooperation by the riparian countries to date and stocks remain overexploited in the Black Sea (Goulding et al., 2014).

In Turkey, the Black Sea fisheries play an important role both in supplying the increasing protein demand of the growing population and by contributing to the gross domestic product through local employment. In 2013, the Black Sea catch corresponded to 62% of the total catch from Turkish seas (including the Sea of Marmara, the Aegean and the Eastern Mediterranean) with 15,000 fishermen corresponding to 45% of the total employment in marine fisheries (TUIK, 2013). The most important fishery in the Black Sea is anchovy and in 2013 with the relatively low catch of 154 ktons amounted to 58% of the total water resources catch within the Turkish Black Sea EEZ contributing ∼249 million Turkish Liras (TRY) to the national income.

Anchovy catches vary greatly from year to year (**Figure 2**). Following over-exploitation of large pelagic fishes, dolphins, and demersals at the end of the 1960s, anchovy became the most abundant and commercially important target species, followed by sprat (*Sprattus sprattus*), the second in abundance (Daskalov, 2003). The total Black Sea anchovy catches in the 1970's oscillated at around 250 ktons escalating in the 1980's to as high as 560 ktons (**Figure 2**). This high anchovy catch regime persisted for a decade due to the extensive bottom-up food supply rendered by the eutrophic ecosystem conditions, and ended with the abrupt collapse of the anchovy fisheries in 1989–1990 (86 ktons). After the collapse, the Turkish anchovy fisheries recovered within a few years and since the early 1990's fluctuated between the range of 120 and 370 ktons while the fishing effort remained much the same (Oguz et al., 2012; STECF, 2015). Interestingly, other anchovy fisheries were not able to recover from the crash in the late 1980's (**Figures 2A,B**).

The Turkish anchovy fishery is based on fishing schools of overwintering anchovy along the Turkish coast during

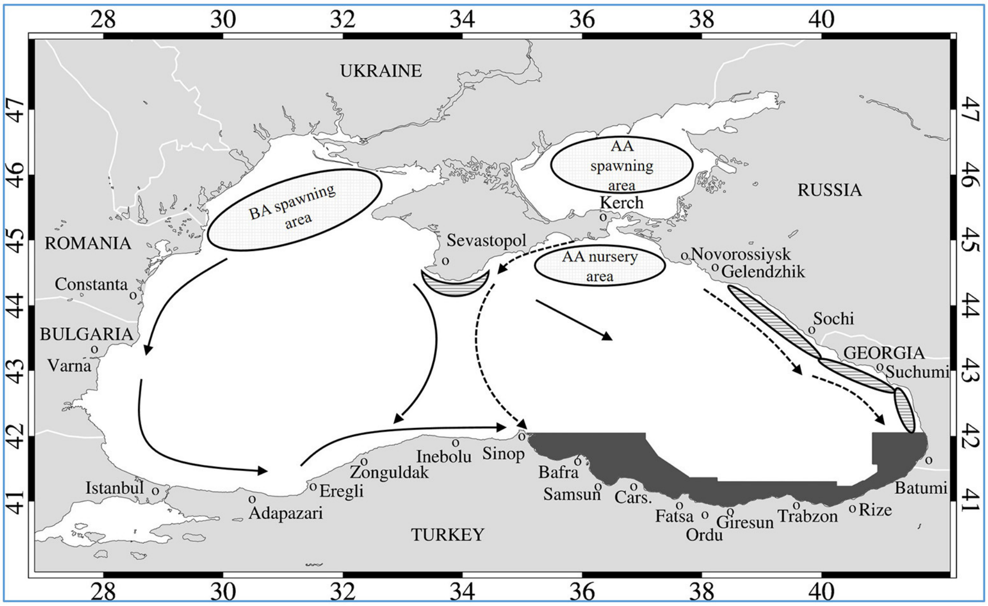

FIGURE 1 | Conceptual figure of Azov anchovy (AA) and Black Sea anchovy (BA) spawning and foraging regions, fall migration paths (indicated by arrows) and overwintering grounds (hatched ovals along Russian and Georgia coasts, as well as the Crimean Peninsula–AA anchovy and gray shaded area–BS anchovy). Redrawn combining concepts of Ivanov and Beverton (1985) and Chashchin (1996).

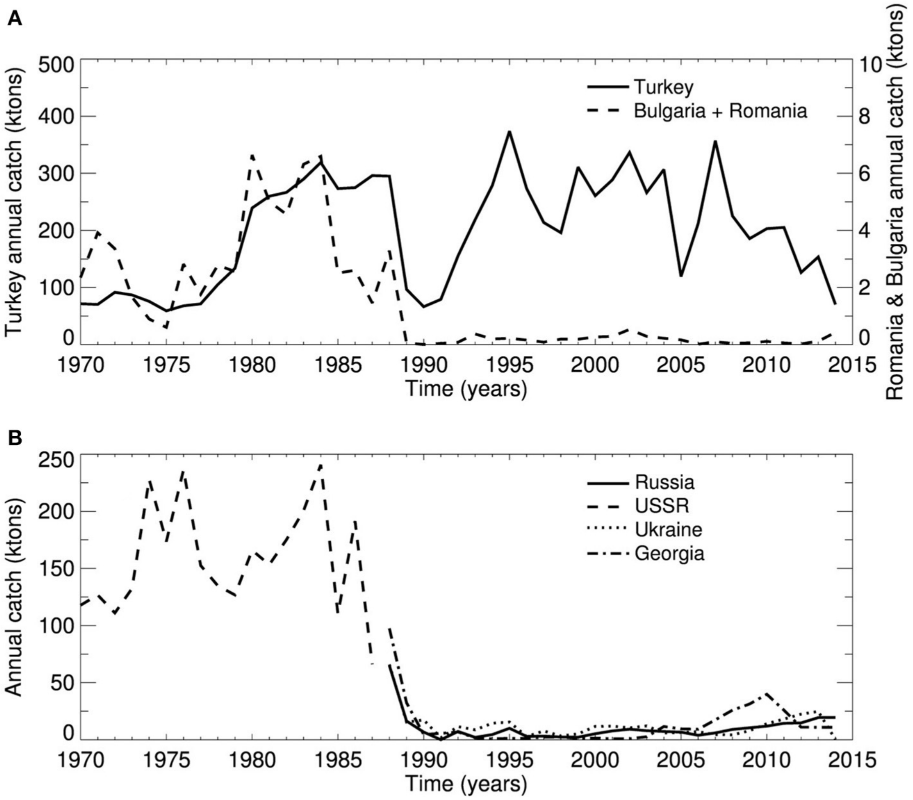

FIGURE 2 | Total annual anchovy landings (ktons) of present and former Black Sea riparian countries from 1970 to 2014 (FAO, 2014). **(A)** Turkey and Bulgaria-Romania combined and **(B)** Russia, former USSR, Ukraine and Georgia.

winter time with purse seiners. The fishing season officially begins on 1st September until mid-April after which industrial fishing is banned for 4.5 months. However, this time period exceeds the actual availability of anchovy in the area which usually peaks between November and December, and therefore is not thought to impact the strong variability of catches. Fishing is restricted to night time only in an effort to control harvest and light fishing is not permitted, however there is no Total Allowable Catch (TAC) in place. In an effort to reduce fishing pressure, the licensing of new fishing boats has been halted since 2015 and a periodic, voluntary fishing vessel decommissioning program has been applied since 2012 (Gucu et al., 2017). High operational costs of the fishing fleet lead to fishermen targeting only large schools of anchovy that enable them to land large amounts of fish in one operation (Gucu et al., 2017) rendering targeting scattered anchovies non-profitable. Georgia's fishing fleet is much smaller (Castilla-Espino et al., 2014) and Georgian fishery enterprises hire a limited number of Turkish purse seiners each year. The fact that anchovy aggregate to form dense schools when overwintering makes them specifically vulnerable to exploitation and potential overexploitation (Auckland and Reid, 1998; Petitgas et al., 2001).

METHODS

In this study, surface geostrophic currents of the Black Sea were calculated from satellite derived Sea Level Anomaly (SLA) data and the mean topography of the Sea. Using these geostrophic currents, a Lagrangian individual based model of anchovy transport was used to simulate anchovy advection across the Black Sea including swimming behavior.

Satellite Data

Black Sea surface circulation fields were calculated using the AVISO+ (*Archiving, Validation, and Interpretation of Satellite Oceanographic data)* Sea Level Anomalies (SLA) and geostrophic velocity anomalies regional product for the Black Sea. They are level 4 delayed time (DT) daily multi-mission sea surface heights anomalies data on a regular 1/8° × 1/8° grid created by a multi-satellite altimetric ground segment named SSALTO/DUACS (*Segment Sol ALTimétrie et Orbitographie)* system operating under Centre National d'Etudes Spatiales (CNES) and made available for use via AVISO+ catalog (http://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/regional/msla-black-sea.html). This daily AVISO data was then interpolated spatially onto a 1/16° × /10° (7 × 8 km) grid and the mean sea surface height (SSH) provided by Korotaev et al. (2003) was added to these fields to compute the absolute dynamic topography (ADT) of the Black Sea. The geostrophic surface currents were computed from these fields (**Figure 3**). Velocities calculated as >0.5 cm/s were assigned to 0.5 cm/s in order to reduce erroneous satellite data at the boundaries. However, it should be noted that this process smooths out offshore jets that are known to extend 100 km from the shelf break and reach velocities of about 70 cm/s (Ivanov et al., 1985 as cited in Oguz et al., 1994).

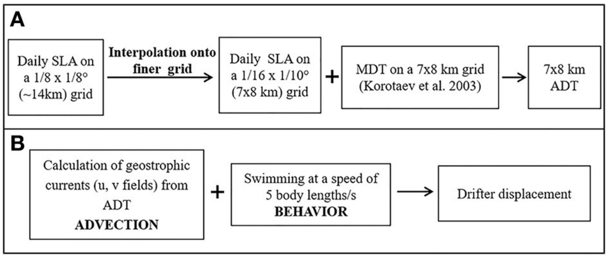

FIGURE 3 | Schematic diagram of data processing and drifter (anchovy) displacement calculation performed in this study: **(A)** Daily Sea Level Anomaly (SLA) fields provided by AVISO+ were interpolated spatially onto a 7 × 8 km grid. The mean dynamic topography (MDT) compiled by Korotaev et al. (2003) was added to the SLA fields to obtain Absolute Dynamic Topography (ADT) fields from which geostrophic currents were computed. **(B)** Anchovy swimming behavior added to advection by currents results in net drifter displacement.

Using surface currents in this model is a valid assumption, since anchovy are known to occupy the warm, upper mixed layer and avoid low temperatures of the Cold Intermediate Layer below (Niermann et al., 1994; Kideys et al., 2000; Satilmis et al., 2003). Chashchin et al. (2015) suggested that factors such as wind direction, sea surface temperature distribution and currents are the most critical factors for Black Sea anchovy migration. The Black Sea circulation is highly variable and dominated by mesoscale eddies, meanders and filaments (Oguz et al., 1994; Oguz and Besiktepe, 1999; Korotaev et al. 2003). Incorporating this variability into our modeling approach by using SSH satellite-derived currents covers most of the effect of winds, salinity, eddy formation and frontal features that are of important features of the Black Sea circulation.

To account for temperature in the surface layer, sea surface temperature data obtained from Gruppo di Oceanografia da Satellite (GOS) was compiled and used in the model. This daily temperature product for the Black Sea was created using Advanced Very High Resolution Radiometer (AVHRR) data optimally interpolated onto a 1/16° × 1/16° grid (http://gosweb.artov.isac.cnr.it/). This data was then interpolated to the same 1/16° × 1/10° (7 × 8 km) model grid resolution as the AVISO data and during transport simulations the ambient sea surface temperature was extracted from this data set.

Fish Movement in the Model

In this study, drifters released in the surface current field resemble adult anchovy schools and a single drifter in the Lagrangian Particle Tracking algorithm follows the Eulerian time integration:

$$\frac{\partial X}{\partial t} = V(X, t) \tag{1}$$

where the particle location is denoted by X at a certain time t and the velocity at location X is represented by V.

Compared to the previous particle tracking study of Black Sea anchovy by Fach (2014), the present study not only considers advection of anchovy but also the swimming behavior of anchovy, such as migration, is included. This is achieved by extending Equation 1 with a behavioral movement term:

$$\frac{dX}{dt} = Va(X,t) + Vb(X,t) \tag{2}$$

where displacement by advection (V_a) and behavioral swimming (V_b) both influence the velocity of a particle at location X and time t. When total velocity (V) acting on the particle is the sum of both behavioral and advective velocities, the integration of equation 2 gives:

$$X\left(t^{n+1}\right) = X\left(t^{n}\right) + \int t^{n}\ V\ (X,t)\ dt \tag{3}$$

Here the time step (dt) is equal to $t^{n+1}-t^{n}$ where n is the index for time chosen as one minute in this study. Forward Eulerian method was used to integrate equation 2 (Parada et al., 2003; Guizien et al., 2006; Lett et al., 2007) and applied as:

$$X^{n+1} = X^{n}\ + V(X^{n},t^{n})dt \tag{4}$$

One major benefit of using this method is that it required only the position (X_n) and one velocity field at the current time step $V(X,\ t^n)$ to estimate the new position X^{n+1} of the drifter. Another advantage of this scheme was its lower CPU requirements compared to the fourth order Runge Kutta scheme.

The main disadvantage of choosing this first order differencing scheme is reduced accuracy which may eventually lead to divergence from real drifter trajectories (Bennett and Clites, 1987). To counteract such errors, the time step should be minimal. Here, the choice of a 60 s time step was small enough to ensure accuracy comparable to a second-order accurate scheme (Fach, 2014).

Parameterization of Anchovy Behavior

Anchovy are known to be sensitive to temperature, it being a key trigger for the onset of migration (Chashchin and Akselev, 1990; Panov and Chashchin, 1990; Panov and Spiridonova, 1998; Berdnikov et al., 1999; Shulman, 2002; Shulman et al., 2008) and are likely to follow temperature gradients to move toward warmer water in overwintering grounds (Chashchin, 1996). Temperature plays a critical role because of the special climatic feature of the Black Sea, where an exceptionally large zonal west-east temperature gradient exists with fall-winter temperatures in the southeastern region being ∼4–5°C higher than the northwestern region (Buongiorno Nardelli et al., 2010; Capet et al., 2012). Anchovy can swim at high speeds of up to five body-lengths/s (bl/s) for long periods of time, as observed in Peruvian anchovy (Peraltilla and Bertrand, 2014), and similar swimming speeds have also been observed in the Black Sea anchovy (A.C. Gucu, pers. comm.). Hence, simulations including anchovy moving along temperature gradients with swimming speeds of 5 bl/s were performed. The mean length of individual adult anchovy in the school is thereby assumed to be 10 cm (Bilgin et al., 2016). In this individual based modeling approach, fish feeding and metabolism are not included, as Black Sea overwintering migration is considered to be a non-feeding migration (Shulman, 2002; Shulman et al., 2008).

Anchovy behavior in the form of movement following temperature gradients was incorporated into the Lagrangian model following the parameterization of Xu et al. (2013) where anchovy pursue a food gradient. Parameterizing fish movement following gradients is a valid method applied in many different studies, such as Huse et al. (2004) for capelin and cod, Tu et al. (2012) for the spawning migration of Japanese anchovy and Wang et al. (2013) for Japanese anchovy in the Yellow Sea. To implement this approach, the daily distance an adult anchovy can swim was calculated and the temperature distribution within the radius of this distance surrounding the drifter location checked for the warmest temperature. The model anchovy swim in that direction and the displacement of the drifter is obtained by adding the behavioral movement vector to that caused by the advection by currents starting from the drifter's initial position. Selecting the same initial position for both behavioral movement and advection is a reasonable assumption supported by an earlier sensitivity study done by Xu et al. (2013).

Internal fat storage accumulated during the pre-wintering season is suggested to be preparing anchovy for overwintering migration (Shulman, 2002; Shulman et al., 2008). Therefore, we assume for the model purpose that only those anchovy that accumulate enough reserves are able to start migration. With the onset of cooling, Black Sea and Azov Sea anchovy stop feeding, aggregate in large schools and then begin migration (Chashchin et al., 2015). In this study, the actual schooling behavior is not incorporated in the model. We assume that each drifter that is released represents an already aggregated school of anchovy with the necessary fat levels enabling them to perform the long-distance overwintering migration. Since this study focuses on modeling the overwintering migration of adult anchovy schools (from here on they will be referred to as "drifters") to the overwintering grounds, all drifters reaching the narrow shelf region of the southern Black Sea (≤1,500 m) east of 35°E longitude (**Figure 1**, gray shaded area) were considered as drifters which achieved a successful migration.

Design of Simulations

To understand the impact of climatic variability on anchovy migration success, several sets of simulations were undertaken. A total of 7,176 Lagrangian drifters resembling anchovy schools were released in the surface circulation field of the Black Sea on October 30th of three different years (2001–2003) and tracked for 2 months. Of these, 1,026 drifters were released in the northwestern shelf (NWS), 179 off Kerch Strait, and the rest in the entire Black Sea. To test different environmental conditions in consecutive years, the years 2001 to 2003 were chosen after the analysis of satellite data spanning two decades, the 1990's and 2000's. The data sets revealed that 2001 was an exceptionally warm year, particularly in summer, with strong stratification mainly because of reduced wind stress in the winter of 2000–2001 (McQuatters-Gollop et al., 2008; Buongiorno Nardelli et al., 2010). The year 2002 was average in terms of temperature distribution and 2003 was remarkably cold when compared to the mean conditions, with significantly higher wind stress (McQuatters-Gollop et al., 2008). Based on this analysis and to compare results with the previous study of anchovy larval dispersal, (Fach, 2014) the years 2001 to 2003 were chosen in order to investigate the upper and lower extremes of environmental variability in the Black Sea, respectively. Incidentally, 2001–2003 also correspond to high anchovy catches of around 300 kton (**Figure 2A**).

Two sets of simulations in which particle displacement is due to (a) only horizontal advection by surface currents and (b) movement toward the highest temperature with 5 bl/s coupled with advection were run for each of the 3 years (**Table 1**), enabling the model to assess the impacts of merely physics and of specific behavior on migration success. For model sensitivity analysis, additional simulations using 1, 3 and 6.65 bl/s swimming speeds were undertaken. In the simulations presented here, it is differentiated between Black Sea anchovy, as the dominant species fished by Turkish fisheries assumed to spawn mainly on the NWS of the Black Sea, and Azov Anchovy that spawns in the Azov Sea and enters the Black Sea for overwintering through the Kerch strait.

Anchovy most likely begin overwintering migration depending on the temperatures in October (Chashchin and Akselev, 1990; Panov and Chashchin, 1990; Panov and Spiridonova, 1998; Berdnikov et al., 1999; Shulman, 2002; Shulman et al., 2008) and body fat content (Shulman, 2002; Shulman et al., 2008) but may start migration much earlier than October, as early as mid-September (A. C. Gucu, pers. comm.). Therefore, in a second set of simulations, drifters were released at three different times, September 15th and 30th and October 15th of 2003 to explore seasonal variability. The choice of the year 2003 was made as migration success was the highest of all 3 years and the pathways showed a diverse pattern encompassing a larger geographical area from where drifters could reach the overwintering area compared to the results of the other simulated years.

To ensure a sufficient number of drifters were tracked from different areas of the Black Sea in each simulation for reasons of impartiality, a statistical reliability test was performed. Results obtained by tracking 1,026 drifters released from the NWS were compared with similar simulations that released 7,888 drifters in the same region on October 30th of 2001, 2002, and 2003 with swimming speeds of 1, 3, 5 and 6.65 bl/s in the temperature gradient simulation setup. Results of this analysis showed the % difference in migration success between the simulation results with 7,888 vs. 1,026 drifters to be very low: 0.1, 0.5 and 0% with a swimming speed of 1 bl/s, 0.3, 0.1, and 0.2% at 3 bl/s and 1.4, 0, 0.5% at 5 bl/s in the years 2001, 2002, and 2003, respectively (**Table 2**). It was found that the results between both simulations do not differ significantly. In addition, the mean distance traveled by drifters was examined with the difference between high and low numbers of drifters between <1 km to 30 km, which is rather small considering the total distances traveled (0.2–3.2%). Hence, tracking small numbers of anchovy in the simulations is a reasonable choice helping reduce CPU requirements and run time.

TABLE 1 | List of model simulations.

Interannual variability-start October 30th	Figure/Table
Advection only	**Figures 7**, **8A–F**, **9A–C**
Temperature gradient following with 1, 3, 5, and 6.65 bl/s	**Table 2**
Temperature gradient following with 5 bl/s	**Figures 7**, **8G–L**, **9D–F**, **Tables 2**, **3**
Seasonal variability-start September 15, 30, and October 15	
Advection only	**Figures 10G–L**, **Table 4**
Temperature gradient following with 5 bl/s	**Figures 10A–F, M–R**, **Table 4**

Model results are compared to available data on anchovy overwintering migration (Chashchin, 1996; Chashchin et al., 2015) as well as anchovy distribution along the Black Sea coast from recent, multi-year, acoustic and landing surveys (Gucu et al., 2016, 2017). However, the lack of available, long-term anchovy spatial distribution data and anchovy migration observations make it difficult to perform an in-depth model validation.

RESULTS

Environmental Conditions of the Black Sea

The year 2001 was exceptionally warm, with a mild winter followed by a very warm summer compared to other years in the 1990s and 2000s (McQuatters-Gollop et al., 2008; Fach, 2014). High mean SST's of 28°C in the eastern Black Sea were observed in July–August and decreased only slightly in August–September 2001 (24–26.5°C). The year 2002 was average in terms of temperature distribution 2003 was the coldest year in this study with SST's lower throughout most of the year than the mean SST's of the years 1997–2005 (McQuatters-Gollop et al., 2008). Maximum temperatures in July-August were significantly lower than the previous years (23–25.5°C) and August-September SST's were similar to those in 2002 (22–25.5°C), but with colder temperatures moving in from the north (Fach, 2014).

In an effort to explore the environmental conditions observed by migrating anchovy and how they may influence migration behavior and success, a summary of the SST and geostrophic surface currents in combination with SSH during November of all 3 years is presented. November is the most important month for migrating anchovy in this modeling study when direction of movement is shaping the migration routes. Further analysis of September and December is not presented here but can be found in Guraslan (2016).

Analysis of mean SST's over the entire Black Sea indicated distinct differences in the cooling process among the years of interest, in terms of timing (onset) and rates (development over time) that had implications for the migration of anchovy. Mean SST's in 2001 were highest in September (23.7 ± 0.81°C) and October (19.9 ± 0.94°C) with respect to 2002 and 2003 whereas December 2001 (10.0 ± 0.99°C) displayed the lowest SST's among all years. A sharp drop in the monthly mean SST occurred between October and November equivalent to 5.5°, 4.5°, and 5.1°C in the years 2001, 2002, and 2003, respectively.

TABLE 2 | The results of the statistical reliability study releasing 1,026 vs. 7,888 drifters from the northwestern Shelf on October 30th in years 2001, 2002, and 2003 in the temperature gradient simulations with 1–6.65 bl/s swimming speed for anchovy of 10 cm size.

1,026 Drifter					7,888 Drifter				
Swimming Speed (bl/s)	**Year**	**Arrival numbers**	**Total Success (%)**	**Mean distance traveled (km)**	**Swimming Speed (bl/s)**	**Year**	**Arrival numbers**	**Total Success (%)**	**Mean distance traveled (km)**
1	2001	12	1.2	450.7 ± 221.9	1	2001	103	1.3	451.5 ± 221.5
	2002	3	0.3	584.8 ± 250.9		2002	61	0.8	600.0 ± 240.5
	2003	0	0.0	632.1 ± 236.4		2003	1	0.0	651.9 ± 215.8
3	2001	40	3.9	664.1 ± 484.1	3	2001	330	4.2	686.2 ± 488.7
	2002	278	27.1	927.3 ± 525.5		2002	2129	27.0	944.0 ± 511.1
	2003	10	1.0	918.2 ± 592.4		2003	63	0.8	948.0 ± 582.1
5	2001	125	12.2	421.0 ± 315.8	5	2001	1071	13.6	434.8 ± 315.4
	2002	0	0.0	631.2 ± 346.5		2002	2	0.0	644.4 ± 340.7
	2003	157	15.3	743.2 ± 499.1		2003	1165	14.8	748.6 ± 483.1
6.65	2001	13	1.3	300.0 ± 223.1	6.65	2001	98	1.2	307.3 ± 222.3
	2002	0	0	471.0 ± 313.7		2002	0	0	477.0 ± 325.4
	2003	17	1.7	549.7 ± 335.4		2003	141	1.8	556.4 ± 331.6

This is of importance as the main external trigger for anchovy to start migration is the cooling (i.e., sudden drop of temperature; Chashchin and Akselev, 1990; Panov and Chashchin, 1990; Shulman et al., 2008). However, not only the onset of cooling but the cooling patterns may also have an effect on the fate of migration as it is assumed that anchovy follow temperature gradients toward warmer regions.

In November 2001, after autumnal cooling commenced, the temperature distribution in the Black Sea showed a cold SST signal expanding over the basin excluding the Batumi Gyre area and southern coastal areas (**Figure 4**). The inner basin thereby displayed cooler temperatures (around 10°C) than the NWS. The cooling resulted in a northwest-southeast gradient over the basin. Simultaneously, November 2001 was also characterized by mesoscale variability in the flow resulting in the formation of many mesoscale eddies (**Figure 4**). Most importantly for migrating anchovy, the Sevastopol anticyclone formed on the NWS, an anticyclone occurred southeast of Crimea and a warm jet formed in the southern coast extending from the overwintering area to the inner basin.

In 2002, cooling started on the NWS in the second week of November and spread across the entire western basin, thereby creating a temperature gradient that was located almost in a W-E direction (**Figure 5**). Later in that month, warmer waters reached the southern and northern coasts of the basin and the Batumi eddy strengthened exhibiting high (∼20°C) temperatures. The surface geostrophic currents were characterized by very structured flow with little mesoscale variability, indicating a strong rim current system around a large cyclonic cell with minor formation of mesoscale eddies.

The temperature distribution for 2003 showed cold temperatures on the NWS and off the Sea of Azov that warmed a little in the second week of November and then continued cooling in the western basin, creating a northwest-southeast temperature gradient (**Figure 6**) similar to 2001. The Batumi gyre was not well-defined and characterized with lower temperatures than in the other 2 years. This year was characterized by high mesoscale variability, especially within the western basin. The occurrence of the Sevastopol eddy at the shelf break zone and the anticyclone southeast of Crimea should be noted. In addition, the Sinop anticyclone generated a jet which extended into the inner basin from the south coast especially in weeks 3 and 4 of November (**Figure 6**).

Interannual Variability in Overwintering Migration

Black Sea anchovy

When drifters representing Black Sea anchovy were released at the end of October on the NWS and tracked for 2 months in the advection only simulation, the results showed that the transport of anchovy from the NWS to the overwintering grounds is not possible given the variability by currents alone and hence migration fails in years 2001, 2002, and 2003 (**Figures 7A–F**).

However, simulation results with anchovy swimming along temperature gradients showed that successful migration is possible in 2001 and 2003, but fails in 2002 (**Figures 7G–I**). In 2001, simulated anchovy followed an almost diagonal path from the northern area of the NWS to final destinations near Sinop and Samsun in the western region of the overwintering area. A total of 125 drifters (12.2%) completed successful migration in this period and amongst those, 96 drifters from the northern part of the NWS reached the overwintering area in 4 weeks (**Figures 7J–L**, **Table 3**). The successful drifters are seen to follow the northern edge of the Sevastopol anticyclone and then another anticyclone located in the southeastern zone of the Sevastopol anticyclone (**Figure 7G**). Drifters approach the

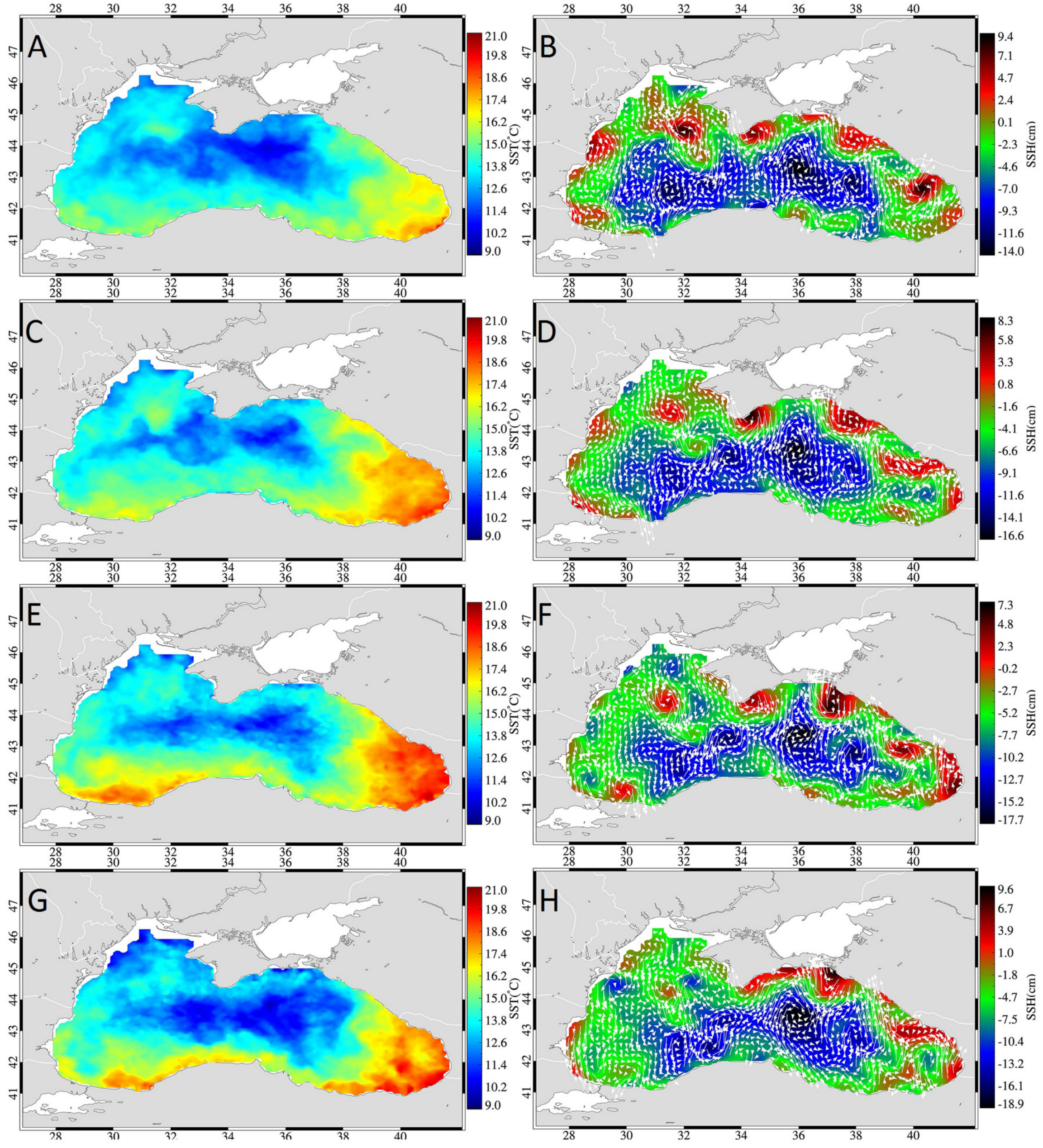

FIGURE 4 | Weekly mean sea surface temperature (left) and sea surface height fields (right) overlaid with geostrophic currents (white arrows) during week 1 **(A,B)**, 2 **(C,D)**, 3 **(E,F)**, and 4 **(G,H)** of November 2001.

southern basin following the south-eastward front formed at ∼15 nm offshore Sinop region during the second and third weeks of November to reach the Sinop region. Subsequently, some drifters follow the warm Rim Current eastwards and reach the Samsun region in the last week of November. Many drifters from the NWS still fail successful migration in this simulation, because of persistently cold temperatures in the interior basin which guide them to the warmer western coastal waters reaching only the Istanbul and Adapazari regions of the west Anatolian coast.

In 2002, none of the drifters completed successful migration to the overwintering area even with application of swimming speed 5 bl/s (**Figure 7H**) due to particularly cold temperatures (19.0–21.0°C) in the second week of November which covered the western basin, leaving a slightly warmer region at the southern edge (**Figure 5C**). Hence, the drifters originating from the Danube and Constansa area followed the warmer Rim Current along the Anatolian coast, reached the closest warm regions between the Bosphorus and Eregli and stayed there. The remaining drifters crossed the basin or followed the eastern

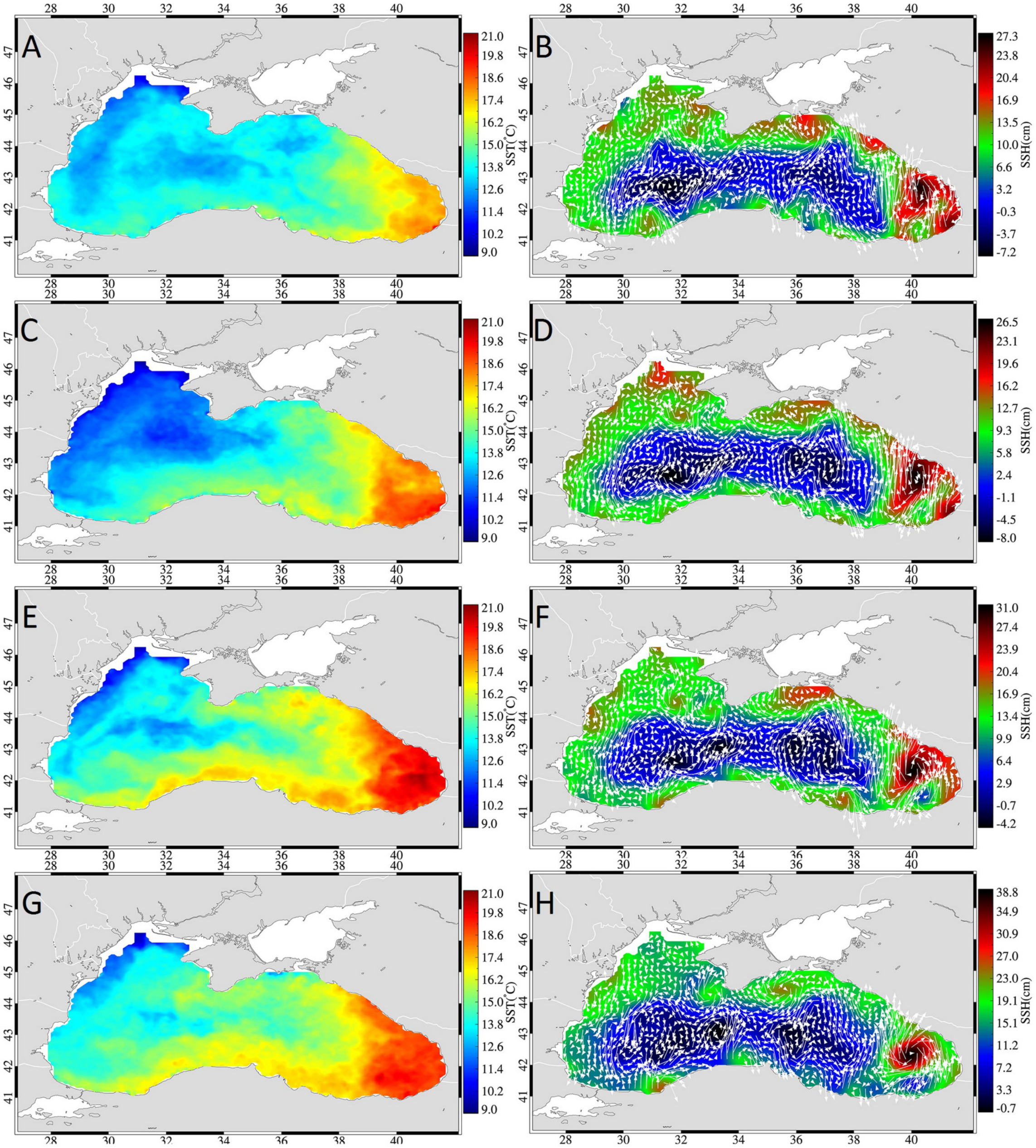

FIGURE 5 | Weekly mean sea surface temperature (left) and sea surface height fields (right) overlaid with geostrophic currents (white arrows) during week 1 **(A,B)**, 2 **(C,D)**, 3 **(E,F)**, and 4 **(G,H)** of November 2002.

edge of the western gyre and also reached the Inebolu region of western Anatolia. In this year, strong flow around the intense western and eastern cyclonic gyres was observed with low mesoscale variability in the surface currents. This facilitated the efficient southward transport of drifters within the western basin, but the regional temperature distribution oriented the migration toward the warm patch off the southwestern coast and therefore no drifters reached the overwintering grounds.

In 2003, temperature gradient following drifters had the highest success rate between all 3 years and a total of 157 (15.3%) drifters reached the overwintering area (**Figures 7I,L**). Among those, most drifters originated from the areas located at the outer shelf between 31.8 and 33.3°E longitudes on the western side of Sevastopol, completing migration in 4 weeks (**Table 3**). Those drifters initially moved south along the warmer edge of the cyclonic formation at the Sevastopol coast in the first week of November and reached the western edge of the warmer Crimea eddy (**Figure 6**). In the second week, they followed the outer edge of the Crimea eddy merging with the central inner basin front carrying warmer waters of the southern basin northwards from

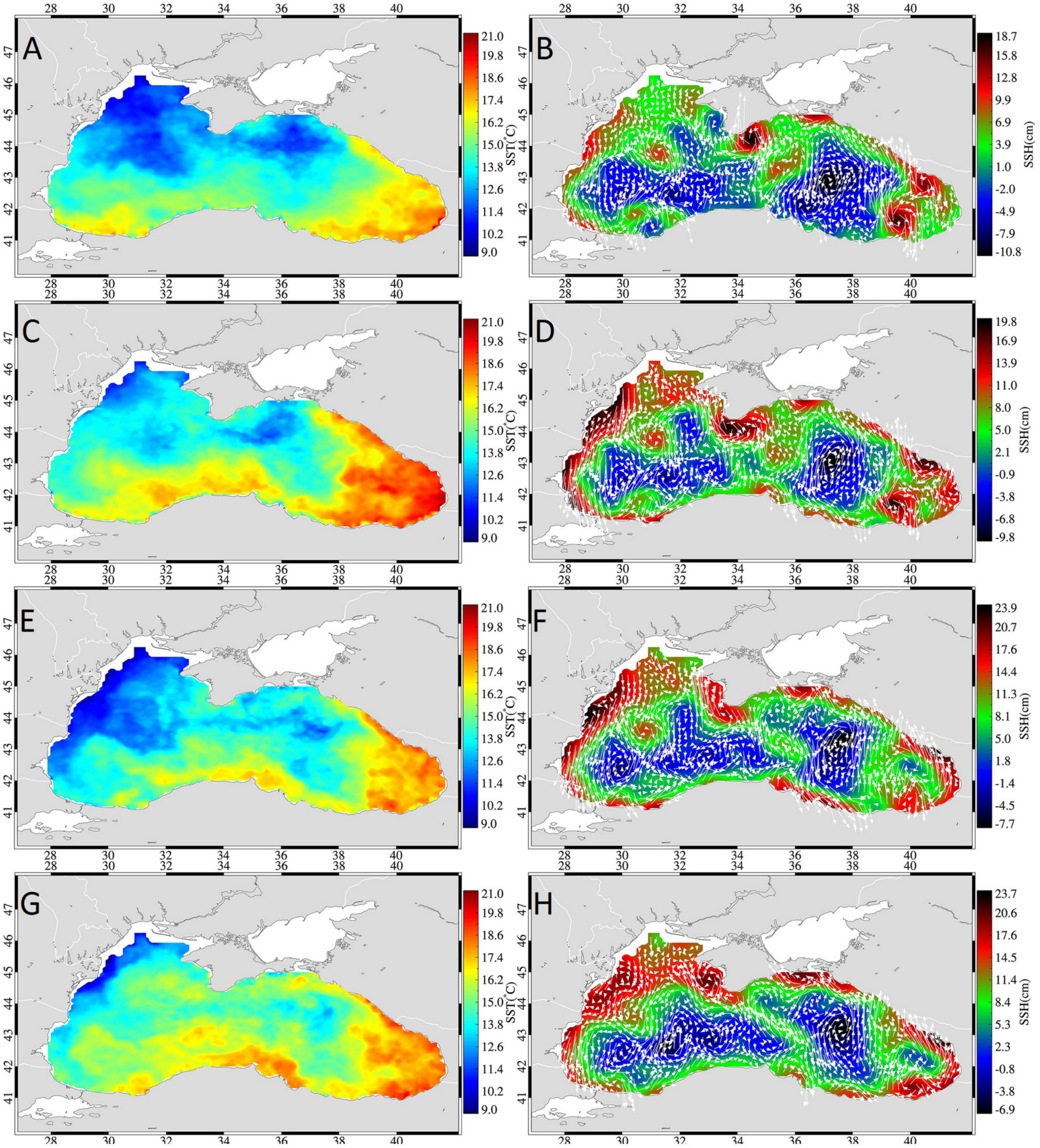

FIGURE 6 | Weekly mean sea surface temperature (left) sea surface height fields (right) overlaid with geostrophic currents (white arrows) during week 1 **(A,B)**, 2 **(C,D)**, 3 **(E,F)**, and 4 **(G,H)** of November 2003.

the Sinop anticyclone to the Crimea anticyclone. On approaching the front at the northern region of the Sinop eddy, the drifters followed the warm waters of the Rim Current and moved along with it eastward. They finally completed their migration at the Carsamba (Samsun) and Fatsa (Ordu) coasts. In addition, some of the drifters that reached the tip of Crimea were observed to move southeastward, then across the Eastern Gyre and proceed to the southern coast of the eastern basin. Drifters from the northernmost areas of the NWS were able to reach the warmest parts of the overwintering area in 8 weeks. They followed the southern edge of the Sevastopol eddy at the shelf break and within the western gyre followed the front between the cyclonic gyres in the interior basin. These drifters reached the Inebolu region veering eastward at 42°N and approached the warmest regions of the basin located in the southeastern corner of the Black Sea, the Batumi Region, in 8 weeks. The intense cyclonic activity observed within the western basin, the increased Danube fresh water discharge flow and the strong western gyre are the features that caused retention of the remaining drifters in the western basin, leading them toward the nearest warmer

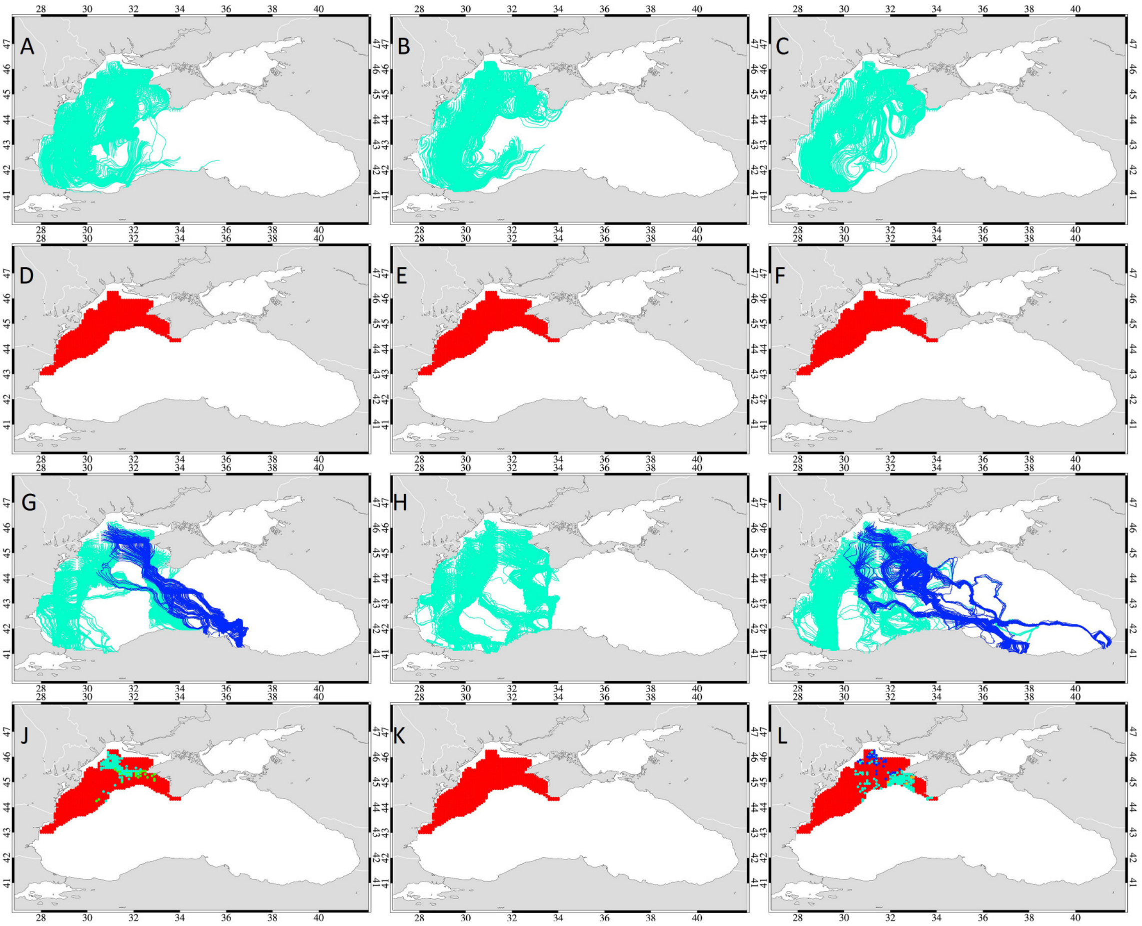

FIGURE 7 | Simulations of interannual variability: The paths **(A–C,G–I)** and start points **(D–F,J–L)** of drifters released on the northwestern shelf at the end of October. Drifters were advected by surface geostrophic currents alone **(A–F)** and followed temperature gradients **(G–L)** swimming 5 bl/s in 2001, 2002, and 2003 (left, middle, and right column). The paths of drifters reaching the overwintering area in 2 months are marked blue, the ones that do not reach are marked green. The start points of drifters that complete a successful migration in 2, 4, 6, and 8 weeks are color-coded green, cyan, yellow and dark blue, respectively. The start points of the drifters that fail to reach the overwintering grounds are marked red.

regions at the Bulgaria, Bosphorus and Zonguldak—Inebolu coasts.

Azov Anchovy

When drifters representing Azov anchovy were released from the Kerch Strait area in the advection only simulation, 34.6, 43.5, and 20.6% of the drifters completed successful migration in 2001, 2002, and 2003, respectively (**Table 3**). This indicates that currents in the eastern part of the basin, though variable from year to year, do actively support transport to overwintering grounds. The specific pathways were along the western periphery of the eastern gyre in all years, whereby the pathway moved slightly east from 2001 to 2003 (**Figures 8A–C**) depending on the location of the Eastern Gyre in that particular year. **Figures 8A–C** details how the currents on the western periphery of the cyclonic eastern gyre connect the Kerch Strait region to the western region of the overwintering area. The average travel times were 6 to 8 weeks in 2001 and 8 weeks in both 2002 and 2003 (**Figures 8D–F**, **Table 3**).

Contrary to advection only simulation, in the temperature gradient simulation, the pathway orientation, migration success and the location of the source regions of drifters that complete a successful migration from Kerch region to the overwintering area experienced significant interannual variability (**Figures 8G–I**). Migration success is very low in 2001 (%7.8), low in 2002 (%24.5) but very high in 2003 with a 92.7% success rate (**Figures 8J–L**, **Table 3**). This strong variation is caused by the interannual variability in temperature distribution in the eastern basin apparent when analyzing the pathways of successful drifters.

In 2001, two possible pathways were identified: (i) midway between western and eastern gyres from source regions close to Crimea. Migration took only 2 weeks (**Figure 8J**), (ii) Movement along the east coast of the Black Sea to the Novorossysk region and further by offshore drift toward the Trabzon region and then to the Batumi region in 6 weeks. In 2002 the most successful drifters originated from the eastern sector of the release area and

TABLE 3 | Migration success of drifters released on October 30th in years 2001, 2002, and 2003 from the northwestern shelf, Kerch Strait exit region and the entire basin in the advection only and the temperature gradient simulation with 5 bl/s swimming speed.

Simulation	Release area	Drifter number	Year	Speed	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %
Advection only	NW Shelf	1,026	2001	0	0	0	0	0	0	0
			2002		0	0	0	0	0	0
			2003		0	0	0	0	0	0
Temperature gradient following	NW Shelf	1,026	2001	5	29	96	0	0	125	12.2
			2002		0	0	0	0	0	0
			2003		0	121	4	32	157	15.3
Advection only	Kerch exit	179	2001	0	0	0	7	55	62	34.6
			2002		0	0	0	78	78	43.5
			2003		0	0	0	37	37	20.6
Temperature gradient following	Kerch exit	179	2001	5	8	2	4	0	14	7.8
			2002		5	37	0	2	44	24.5
			2003		6	28	61	71	166	92.7
Advection only	Entire basin	7,176	2001	0	104	191	204	851	1350	18.8
			2002		72	30	3	369	474	6.6
			2003		45	44	15	1,005	1,107	15.4
Temperature gradient following	Entire basin	7,176	2001	5	1,722	481	136	0	2,339	32.5
			2002		1,975	711	7	2	2,695	37.5
			2003		2,303	373	327	104	3,107	43.2

the majority completed migration in 4 weeks (**Figure 8K**). The successful drifters followed a third (iii) diagonal open ocean path from the Novorossysk region to the western (Bafra—Carsamba) section of the target area. They proceeded to move further east toward the Batumi region at 42°N latitude and approached the warmest areas of the basin at the Turkish—Georgian border in 4 weeks. In 2003, the western and eastern pathways previously identified in 2001 (the year of moderate mesoscale variability) reappeared with connections between them (**Figure 8I**). More than half of the successful drifters migrated south along the eastern Black Sea coast, moving partially against the flow associated with the rim currents in this region. These drifters took 6–8 weeks to arrive in the overwintering region, while those migrating along the western periphery currents of the eastern gyre appeared in 2 to 4 weeks (**Figure 8L**).

Entire Basin

Analysis of drifters released throughout the entire Black Sea in the advection only simulation portray the regions from where drifters can be advected to the overwintering area as the mouth of the Kerch Strait, along a longitudinal transect between the Sea of Azov and the Anatolian coast, the central coast of Anatolia in 2001 and in addition the Batumi region in 2003 (**Figures 9A–C**). Migration took between 4 to 8 weeks and varied significantly between years, with most drifters arriving in 2001 (18.8%), 15% in 2003 and only 6.6% in 2002 after different migration times (**Table 3**). The low success in 2002 is due to the well-organized cyclonic current flow around the interior basin which reduced retention in this area.

In the temperature gradient simulations (**Figures 9D–F**), the migration success increased significantly (32.6–43%) and the migration duration decreased (**Table 3**). In these simulations, the eastern basin was the dominating source area for successful migration in all simulations. In particular, the southern part of the eastern basin is seen to transport drifters in 2 weeks in all years (**Table 3**). Successful drifters from the northern half of the eastern basin completed migration in 4 to 6 weeks in 2001 and 2002 simulations. However, in 2003, the majority of drifters in the northern half of the eastern basin were faster, completing migration in 2 weeks. It can be seen again, that only in the temperature gradient simulations drifters originating from the NWS were able to arrive at the overwintering area.

In 2001, the source areas supplying anchovy to the overwintering area were located within the open sea regions of the eastern basin (**Figure 9D**). The warmer coastal anticyclonic eddies were retention areas for drifters at the beginning of November when the sites of very high temperatures retreated to the narrow area at the southeastern boundary of the Black Sea. In 2002, drifters in the northern and southern regions of the eastern basin migrated in 2 and 4 weeks. The W-E SST gradient during November 2002 contributed to successful migration of drifters from the eastern basin. Moreover, low mesoscale variability during this time, stronger flow associated with the rim current and around the cyclonic western and eastern gyre in this period established fast transport from north to

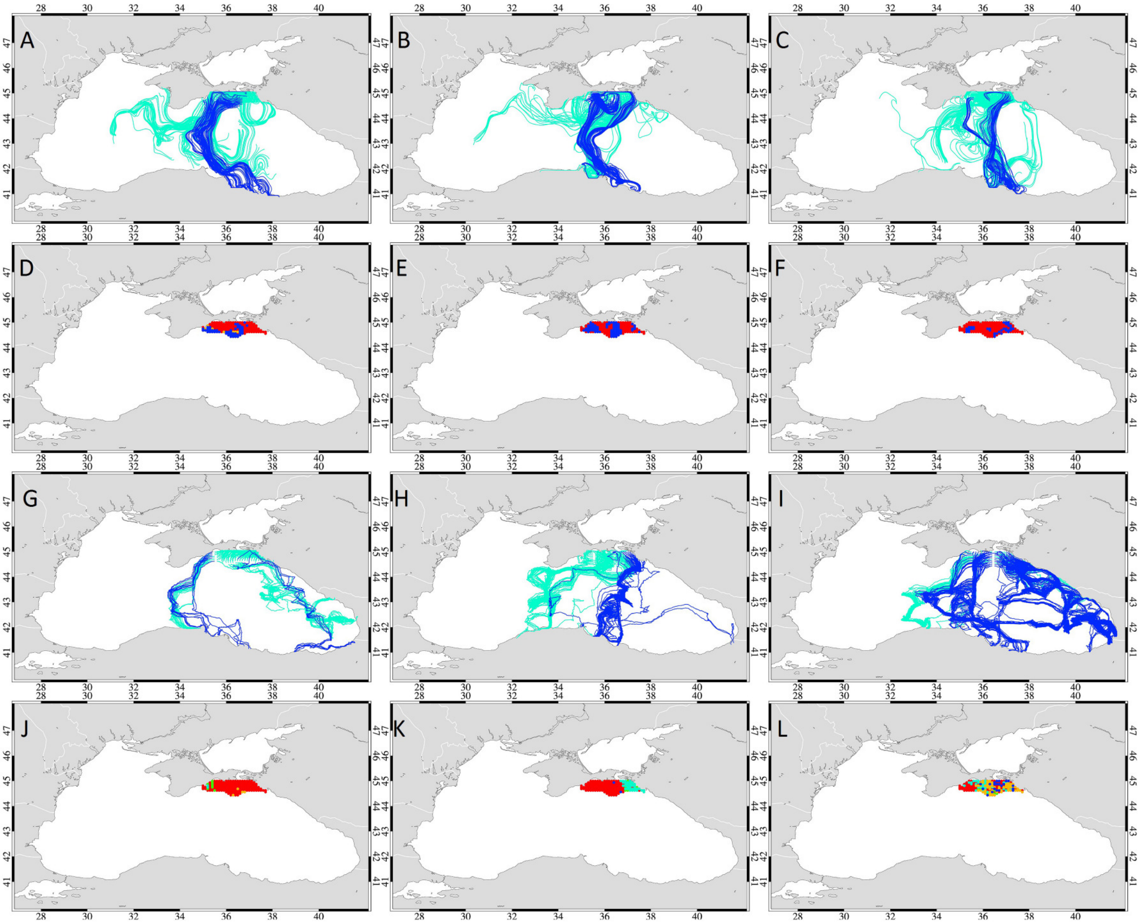

FIGURE 8 | Simulations of interannual variability: The paths **(A–C,G–I)** and start points **(D–F,J–L)** of drifters released at Kerch Strait exit area at the end of October. Drifters were advected by surface geostrophic currents alone **(A–F)** and followed temperature gradients **(G–L)** swimming 5 bl/s in 2001, 2002, and 2003 (left, middle, and right column). The paths of drifters reaching the overwintering area in 2 months are marked blue, the ones that do not reach are marked green. The start points of drifters that complete a successful migration in 2, 4, 6, and 8 weeks are color-coded green, cyan, yellow and dark blue, respectively. The start points of the drifters that fail to reach the overwintering grounds are marked red.

south between the gyres in November 2002. At the beginning of November 2003, the intense cooling that started in the second half of October resulted in decline of the highest temperature regions toward the narrow coastal area in the Batumi region. But in the second half of November, the region of high SST again extended further westwards (38°E) into the eastern inner basin, enabling successful migration of the majority of drifters in only 2 weeks.

Seasonal Variability of Overwintering Migration

The seasonal variability in migration success and pathways was explored by releasing drifters from both the NWS and Kerch Strait regions on three different dates (September 15, 30 and October 15) 2003, the year in which the highest migration success was observed in the temperature gradient simulations.

Similar to the above results, drifters from the NWS representing Black Sea anchovy were unable to reach the overwintering area in the advection only simulation for any of the release dates (**Table 4**), indicating that active swimming behavior is a prerequisite for successful arrival at the overwintering areas. In the temperature gradient simulations a migration success rate of 13.3% for drifters starting in mid-September (**Figures 10A,D**, **Table 4**) was observed, close to the 15% success rate of the reference simulation (initiated on October 30). Successful drifters moved toward the warmer Crimean Peninsula region and approached the warmer southern regions in October by following the warm water margin between the southern edge of Crimea eddy and the small anticyclone at the south. At the end of September, warm temperatures had reached the southeastern coast of Crimea whilst cool SST's approached in October from the northwest with the high SST's retreating toward the south coast. Warm water areas in the southeastern basin then began to retreat toward the eastern coastal areas at the end of October.

However, the drifters that started migration at the end of September (**Figures 10B,E**) or mid-October (**Figures 10C,F**) revealed a very low migration success of 0.2–21.2% (**Table 4**).

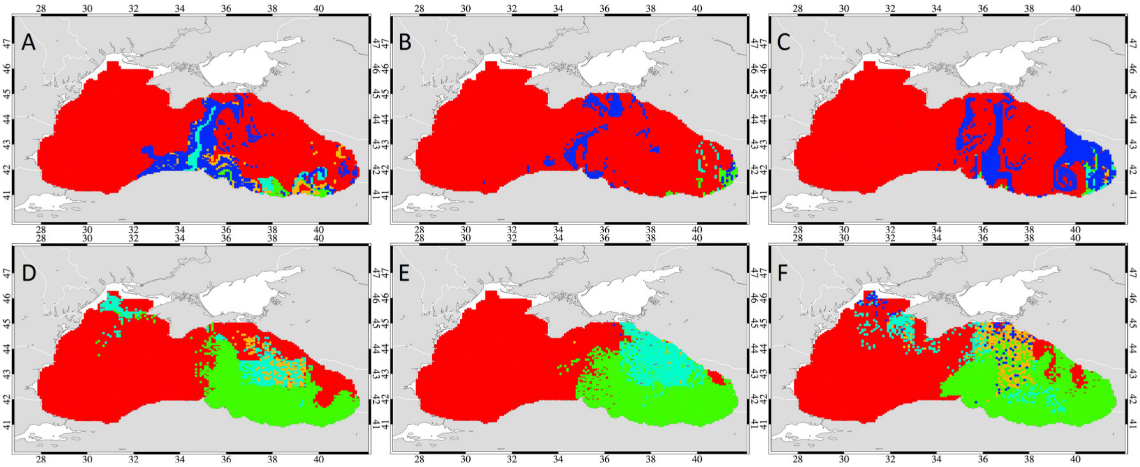

FIGURE 9 | Simulations of interannual variability: The start points of 7176 drifters released at the end of October in the advection only simulation **(A–C)** and in the temperature gradient simulation **(D–F)** in 2001, 2002, and 2003 (left, middle, and right column). The start points of drifters that complete successful migration in 2, 4, 6, and 8 weeks are color-coded green, cyan, yellow, and dark blue, respectively. The start points of the drifters that do not reach the overwintering grounds are marked red.

TABLE 4 | Migration success of drifters released from the northwestern shelf and the Kerch Strait exit region on September 15th, 30th and October 15th 2003 in the advection only and the temperature gradient simulations with 5 bl/s swimming speed.

Simulation	Release area	Drifter number	Start date	Speed	2 weeks	4 weeks	6 weeks	8 weeks	Total arrival	Success %
Advection	NWS	1026	SEPT 15	0	0	0	0	0	0	0
			SEPT 30	0	0	0	0	0	0	0
			OCT 30	0	0	0	0	0	0	0
Temperature gradient following	NWS	1026	SEPT 15	5	0	7	127	2	136	13.3
			SEPT 30	5	0	12	0	0	12	1.2
			OCT 15	5	0	0	2	0	2	0.2
Advection	Kerch exit	179	SEPT 15	0	0	0	0	17	17	9.5
			SEPT 30	0	0	0	0	14	14	7.8
			OCT 15	0	0	0	0	90	90	50.3
Temperature gradient following	Kerch exit	179	SEPT 15	5	3	25	24	0	52	29.1
			SEPT 30	5	0	58	19	1	78	43.6
			OCT 15	5	1	96	6	0	103	57.5
Advection	Entire basin	7176	SEPT 15	0	119	31	27	793	970	13.5
			SEPT 30	0	45	41	63	572	721	10.0
			OCT 15	0	87	33	55	661	836	11.6
Temperature following	Entire basin	7176	SEPT 15	5	1640	997	580	3	3220	44.8
			SEPT 30	5	1839	1163	77	5	3084	42.9
			OCT 15	5	2265	774	58	2	3099	43.1

This was mainly due to the intense cooling in the second half of October (weeks 3 and 4) that produced a strong northwest-southeast temperature gradient, remnants of which remained until the first week of November (**Figure 6A**). Drifters released then therefore did not move toward Crimea and then further south, but headed toward the warmer SST regions in the southeastern part of the western basin which was then the only accessible warm area in the western basin. Concurrently, the warm temperatures at the southern coast further retreated toward the Anatolian coastline and drifters arrived either at the central (Zonguldak—Inebolu) or western (Istanbul) coasts of Anatolia outside the overwintering area.

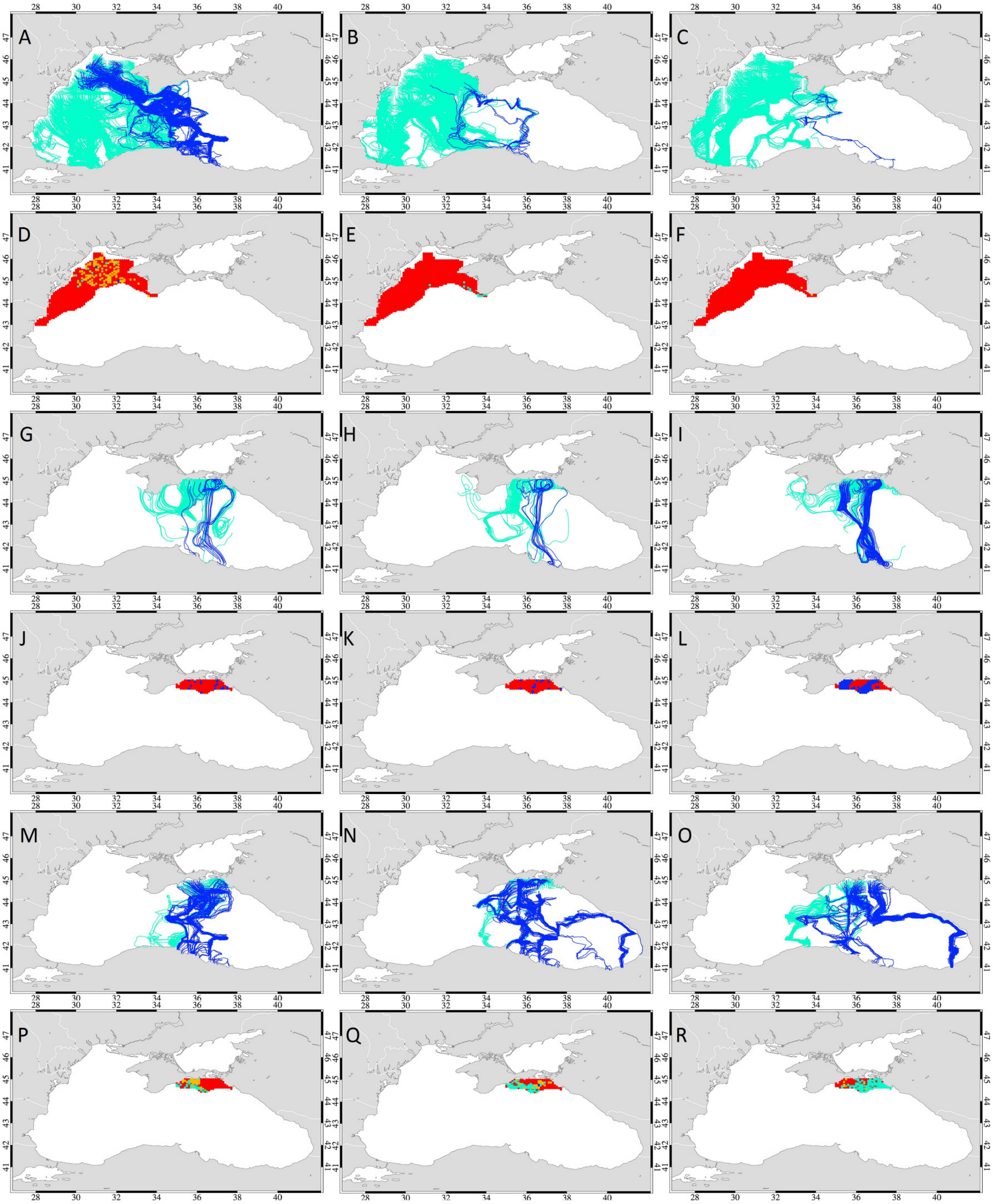

FIGURE 10 | Simulations of seasonal variability: The paths **(A–C)** and start points **(D–F)** of drifters released on the northwestern shelf in temperature gradient simulations. Further, the paths of drifters **(G–I)** and start points **(J–L)** released at Kerch Strait exit area in the advection only simulations and the paths **(M–O)** and start points **(P–R)** of drifters released at Kerch Strait exit area in the temperature gradient simulations. Release times were September 15th, 30th and October 15th in 2003 (left, middle, and right column). The paths of drifters reaching the overwintering area in 2 months are marked blue, the ones that do not reach are in green. The start points of drifters that complete a successful migration in 2, 4, 6, and 8 weeks are color-coded green, cyan, yellow, and dark blue, respectively. The start points of the drifters that do not reach the overwintering grounds are marked red.

Only very few drifters from the tip of the Crimean Peninsula completed successful migration then. Therefore, for drifters originating from the NWS in 2003, it was advantageous to approach the warmer southern basin prior to the start of cooling in October arriving at the SST hotspots as the cooling progressed.

When the drifters representing Azov anchovy were released from the Kerch region in mid and late September and mid-October in 2003 with only advection by currents, successful drifters followed a direct southward path completing migration in 8 weeks (**Figures 10G–L**, **Table 4**). Migration success was 7.8–9.5% for drifters discharged in mid/late September, less than half the success rate of the reference simulation (start date October 30). However, drifters released in mid-October displayed a 5-fold increased success rate with 50% reaching the overwintering area, 30% higher than the results of the reference simulation.

The inclusion of temperature gradient following behavior in the seasonal variability analysis of drifters released from Kerch exit region revealed a series of pathways for successful drifters due to the variability of SST distribution (**Figures 10M–R**). Migration time decreased to 6 and 4 weeks (**Figures 10P–R**, **Table 4**). Although decreased success rate occurred for those released mid- (29.1%) and late-September (43.6%), elevated migration success was found in the simulation starting mid-October with over half of the drifters (57.5%) completing migration to the overwintering area. However, that was still 35.2% less than the reference simulation (92.7%). This comparatively low success rate was again due to the cooling event at the end of October which caused the high SST regions in the southern basin to withdraw toward the Anatolian coastline and those in the south-eastern basin to retreat further. Drifters released on September 15th followed a single pathway (**Figure 10M**) moving southwards to the eastern inner basin through and around the Crimean eddy that carries warm waters northwards around its western edge. Drifters completed migration in 4 weeks following warm SST's extending from the Anatolian coast to the inner basin arriving at the western part of the overwintering area between Sinop and Samsun.

Following discharge on September 30th, the majority of successful drifters completed migration in 4 weeks originating from the southwestern shelf region at the exit of Kerch Strait (**Figure 10Q**). These drifters initially accumulated in the Crimean eddy region where they approached the inner basin. With the onset of cold SSTs approaching from the northwestern basin, a retreat of warm SSTs to the coasts of Rize and Batumi occurred thereby some drifters followed this gradient moving eastward toward the Caucasus coast (Sochi—Sukhumi) region and continued southwards from Sukhumi to Rize coast (by-passing the Batumi coast) to reach the eastern region Trabzon—Rize, of the overwintering area. Other drifters moved toward the Sinop—Fatsa region.

Successful drifters released on October 15, 2003 either moved eastward toward Sochi, following a southward route along the coast to the overwintering area or alternatively directly migrated south arriving in the Sinop region (**Figures 10M,O**). In addition, a few drifters moved westward along 43°N latitude to the western basin deviating southeastward toward the overwintering area to arrive at the Samsun—Carsamba region. This pattern was also previously observed by Chashchin et al. (2015), stating that in winter, a larger portion of the Azov anchovy stock occupy the northeastern basin, while the rest of the stock form dense aggregations in response to the northern wind observed in November and migrate along the east coast to warmer areas, overwintering along the Georgian coast in cold years.

Model Sensitivity

To analyze the sensitivity of model results to the body length of 10 cm specified in this study, a sensitivity analysis of how their migration success from the NWS is affected by body size was undertaken. The average length of migrating adult anchovy is known to be between 8.3 cm (if 0 age class is assumed to start migration) and 13.3 cm (Bilgin et al., 2016). The model simulations presented in the reliability test (**Table 2**) where a total of 1026 drifters were released over the North-western shelf on October 30th in 2001, 2002, and 2003 therefore cover the entire range of speeds that these different sized anchovies may be able to swim. Migration success of the smallest size (8.3 cm) therefore may vary between 0 and 1% when assuming 1 bl/s swimming speed, as it is unable to swim to the overwintering grounds as fast as the 10 cm anchovy (**Table 2**, 0–1.2% success). In addition, when traveling at 5 bl/s this anchovy class travels about 41.5 cm/s, which is in between the success of 10 cm anchovy at the speeds of 3 and 5 bl/s (30–50 cm/s, 0–27.1% success). The largest anchovies may reach 13.3 cm in length and hence their swimming ability surpasses the 10 cm anchovy. Despite the logical assumption that this makes the larger anchovy likely to be more successful than the 10 cm anchovy at 1 bl/s and at 5 bl/s, simulations showed that moving at 66.5 cm/s instead of 50 cm/s actually severely decreased migration success to 0–1.7%, comparable with the 1 bl/s simulation for the 10 cm anchovy (**Table 2**). This is because of the cooling event in November starting on the NWS in each year of the simulations whereby the ability to swim fast led drifters toward higher temperatures in the southwestern Black Sea coast, which were then isolated from the warmer waters in the southeastern Black Sea and hence missed the opportunity to migrate toward the warmest waters located in the southwestern Black Sea coast/Batumi region.

It can be concluded that the model is sensitive to the size of anchovy migrating as it translates effectively into migration speed. A smaller sized anchovy may be slightly less successful reaching overwintering grounds from the NWS, while a larger animal can possibly reach the grounds faster. However, as mentioned above, it is important to note that swimming speed alone does not determine migration success rate in the model but largely the temperature distribution in the Black Sea, as well as the prevailing currents at the time of migration. In 2001, the success rate was 1.2, 3.9, 12.2, and 1.3 % with 1, 3, 5, and 6.65 body-lengths per second swimming speed (**Table 2**) respectively and similarly, in 2003, the success rate was 0, 1, 15.3, and 1.7 % with speeds of 1, 3, 5, and 6.65 bl/s, respectively. During these 2 years, which at the same time are also characterized by moderate (2001) and high (2003) mesoscale variability in currents, the migration success increased with accelerating swimming speeds. Especially, increasing swimming speed from 3 to 5 bl/s improves the success rate by 8.3 (2001) and 14.3% (2003). The key to successful migration here was the timing and the extent of the northwest-southeast temperature gradient developing in the Black Sea during October due to cooling on the NWS (**Figures 4**, **6**). However, in 2002, the year with lowest observed variability, the application of 1 and 5 bl/s swimming speeds reveal 0.3 and 0 % migration success, respectively, whereas 3 bl/s resulted in the highest migration success of 27.1% among all simulations in which the drifters were released from the NWS. At the same time, the mean distance traveled increased by 213.4, 342.5, and 286.1 km for all simulations using 3 bl/s. In 2002 the entire western basin cooled significantly (**Figures 5A,C**) and a strong west-east temperature gradient formed, rendering warm regions in the western basin unreachable by anchovy, no matter how high the swimming speed (**Table 2**). Therefore, while migration success in this model is sensitive to swimming speed which may also be dependent on body length, temperature distribution in the Black Sea as well as current flow can override this influence.

DISCUSSION

Source of Anchovy Reaching Overwintering Region

In this study, model simulations were undertaken to elucidate the impact of environmental factors, such as sea surface temperature distribution and geostrophic surface flow on the overwintering migration of anchovy in the Black Sea. Simulations including anchovy behavior in the form of swimming along temperature gradients clearly showed that even with speeds of 5 bl/s, anchovy migration success rates for all 3 years studied were only between 0 and 15.3%, indicating that the spawning and nursery areas on the NWS are not likely to play a major role in supplying anchovy to overwintering grounds in this modeling approach within the time frame of the present study. Calculations for all three years of simulations revealed only 4.3% of anchovy originated from the NWS, 2.8% originating from a small area at the very north of the NWS and 1.5% from a larger area to the south. Simulations showed that 95.7% of anchovy arriving at the overwintering area originated from elsewhere in the Black Sea, more specifically from the eastern Black Sea (75%), the northern area of the eastern Black Sea including the Kerch Strait region (16%), and east of Crimea (4.7%) (**Figure 11A**). These findings suggest that anchovy overwintering at the eastern Anatolian coast originate mainly from the eastern Black Sea. These regions lie outside the traditionally accepted main spawning and nursery ground in the Black Sea (**Figure 1**), however spawning in the northeastern Black Sea is well-documented (Ivanov and Beverton, 1985; Chashchin, 1996; Chashchin et al., 2015). We hypothesize that if anchovy from the NWS cannot migrate successfully to the overwintering area in great numbers, but aggregations of migrating anchovy continue to arrive and are fished annually, this may mean that anchovy in the eastern Black Sea spawn successful enough to be able to sustain this overwintering population. This is also supported by studies indicating anchovy spawn successfully over much of the southern Black Sea (Einarsson and Gürtürk, 1960; Niermann et al., 1994; Kideys et al., 1999; Gucu et al., 2016).

Anchovy Migration Pathways

For those anchovy schools that migrated successfully from the NWS, three different pathways were identified (**Figure 11B**): (1) movement from Crimea to the southern Black Sea coast midway between the western and eastern cyclonic gyres (in 2001 and 2003) and (2) through the western gyre (in 2003). An additional pathway (3) was identified within the eastern basin in which anchovy first traveled in the Crimea eddy, reaching the southern waters of the eastern basin by migrating across the eastern gyre (in 2003). Variations of these pathways appeared due to the yearly variability in gyres and eddies (**Figure 11B**, dashed lines). Except for the direct transport pathway between the eastern and western gyre, the identified pathways were seen to change on a yearly basis and were more complex than the migration routes suggested earlier by Ivanov and Beverton (1985) and Chashchin (1996) (see **Figure 1**).

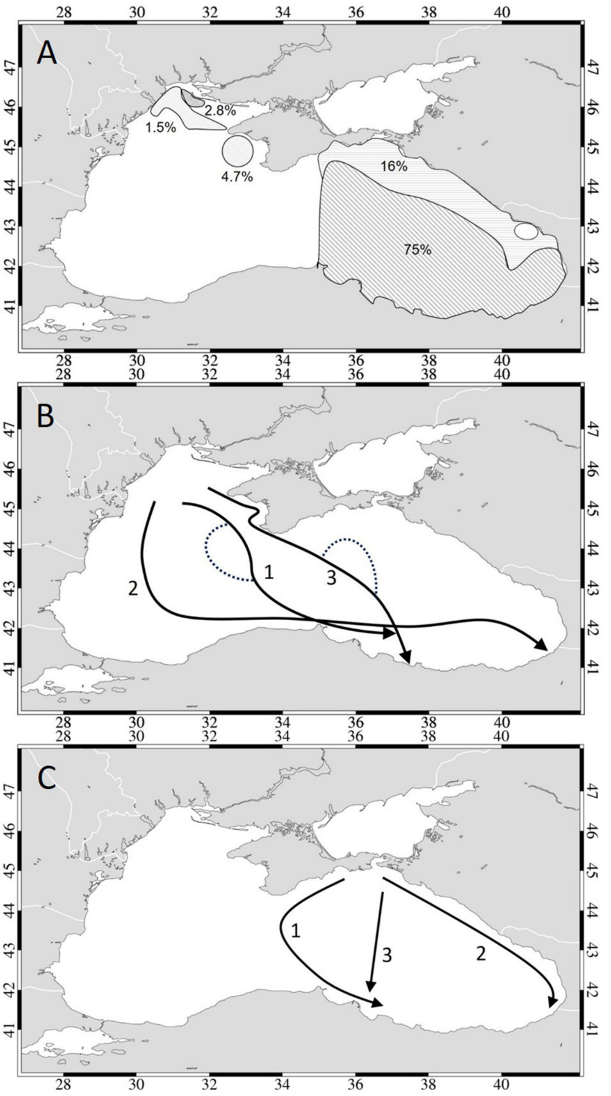

FIGURE 11 | Conceptual figure of **(A)** the regions from where anchovy can successfully reach the overwintering area when swimming along temperature gradients indicating the success rate of migration (%) from each region, showing the migration pathways identified for **(B)** Black Sea anchovy released from the northwestern shelf and **(C)** Azov anchovy released from the Kerch exit region.

It is important to note that migration along the Bulgarian/Romanian coasts did not appear in any of the temperature gradient simulations for different years and start dates, in contrast to Ivanov and Beverton (1985) and Chashchin et al. (2015) who state that the most important fall migration route is the one following the western coast of the Black Sea. Anchovy landing data (**Figure 2**) shows that the anchovy fisheries in Bulgaria and Romania collapsed alongside other anchovy fisheries in the Black Sea in 1989/90 (FAO, 2014; STECF, 2015). Whilst the Turkish anchovy fishery recovered within a few years to reach pre-collapse stock levels, so far there are no reported recovery signs for the Bulgarian/Romanian anchovy fisheries. It has been acknowledged the lack of recovery of the Bulgarian/Romanian fisheries may be in part due to reduced fishing efforts by those countries after becoming EU member states in 2007 and the subsequent application of EU fishing regulations (STECF, 2015; Gucu et al., 2017). However, the complete lack of recovery prior to 2007 has also been hypothesized to be partly due to either a change in spawning areas or changes in migration routes (STECF, 2015; Gucu et al., 2017).

The results of this study indicate that the environmental conditions of temperature and surface circulation during the study period (2001–2003) caused anchovy not to migrate along the Bulgarian-Romanian coasts at all when following temperature gradients, providing the temperature distribution in the Black Sea during autumnal cooling as possible explanation for why this route may be chosen less by migrating anchovy. It may even be possible that a shift in temperature distributions or currents in response to cooling events prevents recovery of this fishery since it caused anchovy to migrate to overwintering regions via open ocean pathways. However, to verify this hypothesis an investigation of long-term satellite data is needed. Furthermore, in warm years, anchovy overwintering along the Crimean coast or other northern areas on the shelf has been reported (Chashchin, 1996; Bingel and Gücü, 2010; Chashchin et al., 2015). Gucu et al. (2017) speculate that apart from inter-specific population dynamics, the actual reason for the "collapse" of the anchovy fishery (in 1989/90, 2007, and 2014) might be that by overwintering outside the known grounds and spending the winter further north in the Black Sea the anchovy was unavailable to the fishery in the southern basin. This points to the urgent need to clarify the prevailing physical conditions during the specific time of migration to be able to manage such fluctuations as has also been suggested by Chashchin (1996).

Anchovy originating off the Kerch Strait, assumed to be representing Azov anchovy in this study, were able to be transported to the overwintering area by currents alone following paths midway between the eastern and western gyre, which agrees well with previous studies (Fach, 2014; Ozturk et al., 2017). From temperature gradient simulations, three major pathways of Azov anchovy were identified (**Figure 11C**): (1) parallel to the eastern Crimean coast and then following the Eastern Gyre reaching the western region of the overwintering area (in 2001 and 2003), (2) diagonally from the eastern zone of the Kerch exit area to the western section of the overwintering area (across the Eastern Gyre) (in 2002), and a third path (3) parallel to the east coast against the flow of the rim current (that carries warm waters of the south northwards) (in 2001 and 2003). However, depending on the proximity of the Rim Current to the east coast, in 2001 the pathway is shifted offshore whereas in 2003 the pathway runs close to the shore and reaches the Georgian coast. These findings are in agreement with observations of Chashchin et al. (2015) who state that in cold years anchovy aggregations move along the Caucasian coast and approach the Turkish—Georgian border. In addition, migration toward the Crimean Peninsula is observed although it is thought to be less frequent and as a consequence more anchovy may be found at the Caucasus coast than the Crimean (Chashchin et al., 2015). However, our modeling results suggest that this pathway is dependent on the occurrence of a strong temperature gradient at the Kerch Strait region and the extension of warm water along the east coast and hence did not occur very frequently. Instead, southward migration in the inner basin between the two cyclonic gyres (pathway 1, **Figure 11C**) was observed in both 2001 and 2003, as well as in the seasonal simulations. However, the suggested migration toward the tip of the Crimean Peninsula by anchovy released from the Kerch Strait region was observed in most simulations of this study within the time frame considered, though was not marked as successful migration in the context of this study.

Importance of Cooling Events

In the simulations of movement following temperature gradients, the average travel time of anchovy schools starting migration from the NWS was found to be 2–4 weeks in 2001 but about 4–8 weeks in 2003. In both years, the SST gradient followed a northwest-southeast pattern that helps successful migration to the overwintering area, whereas in 2002 a more west-east SST gradient resulted in failure of migration. That was due to the short cooling period that took place in the second week of November 2002, when cold temperatures approached from the west and prevailed over the entire western basin (excepting the west coast of Anatolia). This incident ultimately decreased the anchovy's opportunity to find warm areas in the southwestern basin. Additionally, the presence of the Sevastopol eddy at the shelf break in 2001 and 2003 facilitated transport of drifters to the overwintering area by increasing thermal gradients in this frontal region. In 2003, the occurrence of unstable jets and filaments along the southern coast extending into the inner basin further increased successful migration.

It should be noted that in the simulations, anchovy migration was facilitated mainly by currents associated with mesoscale eddies along the coastal regions such as the Sevastopol eddy, the Crimean eddy and the anticyclonic eddy southeast of the Crimean eddy, Sinop eddy, Kizilirmak eddy, and Batumi eddy, as opposed to strong currents associated with the rim current. Often an increase in biological activity along such fronts is called the "edge-effect" and most fish have been found to accumulate at fronts (Roberts, 1980; Kleckner and McCleave, 1988; Castillo et al., 1996; Reese et al., 2011). Fish accumulations along fronts are driven by two factors, optimum temperature conditions and increased prey availability at the front (Owen, 1981; Largier, 1993).

The simulation results suggest that the most important factors shaping migration pathways, and their success, are the intensity and timing of cooling events more than the intensity of currents around eddies and the rim current because of their contribution to the formation of temperature gradients across the Black Sea which determine the pathways chosen by the anchovy. The analysis showed that the onset of migration long before intense cooling in October/November may increase migration success from the NWS region. When anchovy start migration later, direct pathways to the southeastern overwintering grounds may be inaccessible hence migration success decreases significantly. Cold winters caused by successive cold, dry wind outbreaks blowing from the northern sector of Euro-Asia associated with strong positive modes of NAO (Polonsky et al., 2007; Valchev et al., 2012) and EA-WR (Kazmin et al., 2010) lead to cold air temperatures and sea-water temperatures of below 6°C on the shelf (Mihailov et al., 2016).

The timing of the onset of cooling together with its distribution across the Black Sea may therefore be one of the mechanisms that can explain the large fluctuations in anchovy landings in addition to the effects of overfishing, such as those observed in 2005 and 2014 (**Figure 2A**) when catches were below 120 ktons, close to the dramatic decline in catch levels of the 1989/1990 period. In 2005, Chashchin et al. (2015) reported accumulations of Black Sea anchovy south of Crimea during the relatively warm winter, which could help explain low catches in the south. Corresponding movement toward south Crimea is observed in all model simulations and when no warm water leads the anchovy south-ward, the model anchovy similarly stay in this region. Regular observation of this migration pathway supports the hypothesis that stock fluctuations may partially be caused by shifts in environmental conditions and consequently possible shifts in overwintering areas.

The ongoing warming trend in the oceanic environment will inevitably impact species distribution and migratory pathways that are dependent on temperature as an external stimulus. A shift in species distribution has already been observed for some fish species in the world's oceans (Dulvy et al., 2000; Genner et al., 2004; Perry et al., 2005; Nye et al., 2009; Punzón and Villamor, 2009; Simpson et al., 2011; Sunday et al., 2015). For Black Sea and Azov Sea anchovy this may mean two things: (1) a shift in spawning grounds to previously unsuitable regions or (2) a delay in the start of overwintering migration or even a halt of migration if the intensity and/or duration of cooling events do not decrease the temperature to a level sufficiently low to commence migration. In this case, it is likely that school formation would cease and anchovy remain dispersed in spawning/nursery areas. This would result in a shift in fishing grounds and fishing effort as dispersed anchovy becomes no longer a profitable target for exploitation by industrial fisheries. Gucu et al. (2016) already suggest the existence of local, non-migrating anchovy populations in the southern Black Sea basin, an area that was previously thought less suitable for spawning. However, the response of fish populations to continued warming is rather complex and non-linear (Guraslan et al., 2014), as anchovy metabolism, spawning and recruitment success are temperature dependent.

It should be noted that the model applied in this study has uncertainties associated with it, such as those resulting from a fixed swimming speed of 5bl/s during the entire migration. Anchovy swimming speeds may vary depending on conditions during migration. Or anchovy may swim on average 3 bl/s for extended periods of time (Gucu et al., 2017), however the model results discussed above do not change significantly in simulations considering this lower swimming speed (Guraslan, 2016). In addition, simulations were run for 2 months, overlooking longer migration times. While this is a valid assumption, as it has been shown that Black Sea anchovy migration times lie well within that time frame (Gucu et al., 2017), variability in migration times is likely. In addition, lack of data on the cues that influence migration is a big factor creating uncertainties in fish movement models (Haas et al., 2004; Roth et al., 2008) which is especially true for Black Sea anchovy migration. Watkins and Rose (2013), suggest in their study evaluating different animal movement models that gradient following behavior, as implemented in the current study, produced the best fish movement analysis in all tested environments, also confirmed by Politikos et al. (2015). This approach has also been proven successful in other studies (e.g., Railsback et al., 1999; Xu et al., 2013). However, Watkins and Rose (2013) also note that the assumptions that fish are able to sense environmental conditions in the neighboring model cells are sometimes questionable. To reduce uncertainties in the modeling approach, it is of importance to validate the model in greater detail than possible within the current study, including detailed density distributions of anchovy during different seasons. However, at this time the modeling community is limited by the lack of available data. One future development may be to include genetic algorithms in an effort to adaptively optimize parameters known to influence migration using artificial evolution (Strand et al., 2002; Utne and Huse, 2012; Watkins and Rose, 2013).

CONCLUSION

In this study, we demonstrate that the Lagrangian modeling approach including fish behavior applied to satellite derived circulation and temperature data can be used to explore the migration of complex organisms such as fish in the marine environment. The modeled anchovy migration pathways are in agreement with general patterns of anchovy migration given in the literature indicating that the physical environment may be a major factor in shaping general migration patterns. Results of model simulations suggest that most anchovy reaching the overwintering area along the eastern Anatolian coast may originate from the eastern Black Sea and not from the northwestern shelf, which has been traditionally assumed to be the main source of overwintering anchovy in the southeastern shelf area. Migration simulation results are used to hypothesize that there may be alternative migration routes to those traditionally accepted, that are caused by environmental variability in the Black Sea, such as the timing and progression of autumnal cooling together with current strength. Such alternative routes can help explain the low catch of the Bulgarian and Romanian fisheries.

The present work shows in detail, how physical processes such as the timing of fall cooling and the intensity of currents and mesoscale eddies can play a critical role in modifying the highly variable small pelagic fish migratory pathways, their migration success and their availability to fisheries given the interannual and seasonal variability. Physical dynamics may be an important factor explaining the strong interannual variability of anchovy catches. For ecosystem-based marine resource management strategies, it is therefore of great importance to understand the variability in parameters of the physical environment and related uncertainties. This study also demonstrates that modeling is a valuable tool in understanding the processes of fish migration, which is difficult to observe with conventional methods. With this tool, complex processes of environmental variability and the impact on migration success of anchovy can be explored to help predict the timing and success of migration for different years which is of crucial importance to fisheries management.

Currently, the modeling approach of this study includes the influence of the physical environment, while the quality of overwintering grounds, adaptive, schooling and homing behavior is neglected. A limitation of this approach is that model results could not be validated against detailed, long-term anchovy survey data for lack of availability. Efforts to develop coupled hydrodynamic-ecosystem models of the Black Sea environment are underway (e.g., Cannaby et al., 2015) as are models that include food-web interactions to derive fisheries management advice (Akoglu et al., 2015; Salihoglu et al., in review). Application of the fish movement model presented here with a fully coupled hydrodynamic-ecosystem model, may be better able to address not only overwintering but also spawning migration behavior exhibited by anchovy in the Black Sea. However, the modeling community is limited by dependable observations. Reliable data on anchovy distribution for model validation as well as data on cues that may influence migration and selection of preferable habitat is crucial in order to reduce the uncertainty of this modeling approach and of future fish movement models to be developed to propose management schemes.

AUTHOR CONTRIBUTIONS

BF and TO conceived and designed the research, BF and CG designed the model. CG implemented and analyzed the model and led the writing of the paper. All authors contributed significantly to the writing of the paper.

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Harvest Strategies for an Ecosystem Approach to Fisheries Management in Western Mediterranean Demersal Fisheries

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The serious overfishing of most Mediterranean stocks demands urgent reforms of the management measures aiming to guarantee the sustainability of resources, notably when compared with the improvement observed in other European areas. The new EU Common Fisheries Policy (CFP) constitutes an excellent opportunity to introduce the changes needed for such a reform. According to this CFP, all European fish stocks should be brought to a state where they can produce at MSY by 2020 at the latest. The CFP also establishes that the objective of sustainable exploitation should be achieved through multiannual plans (MAPs) adopted in consultation with relevant stakeholders having fisheries management interests such as fishermen, non-governmental organizations, and policy makers. Together with the MSY and MAP approaches, the new CFP contains several other measures, directed to guarantee the ecological and socio-economic sustainability of fisheries by means of the implementation of the ecosystem approach to fisheries management (EAFM). With this new perspective, the CFP wants to avoid past failures of fisheries management based on monospecific approaches. This study is a first step toward the application of the EAFM in the Balearic Islands by means of the development of a harvest strategy with defined objectives, targets, limits, and clear management control rules aimed at optimizing socioeconomic and ecological objectives in the framework of the new CFP. Different management scenarios designed to achieve that goal were modeled for the main demersal commercial fisheries from the study area, the bottom trawl, and small-scale fisheries. The work begins with a general description of those fisheries, their main fishing grounds, and assessments of the exploitation status of the main target stocks in order to establish the current situation. Secondly, alternative management scenarios to maximize catch and profits while considering societal objectives were evaluated by means of bio-economic models. Thirdly, management measures were provided based on the previous modeling and discussions with stakeholders. Finally, a monitoring scheme was outlined to assess the progresses of the proposed management actions. This work is intended to be a working example of co-management (fishers, policy-makers, and scientists) in the Mediterranean in the framework of the new EU CFP.

Keywords: fisheries management, stakeholders, bottom trawl fishery, small-scale fishery, stock status, bioeconomic analysis

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INTRODUCTION

As stated in the Regulation No. 1380/2013 on the Common Fisheries Policy (CFP), the European Union (EU) should ensure that the exploitation of marine resources restores and maintains stocks above levels that can produce the maximum sustainable yield (MSY) by 2015 whenever possible or by 2020 at the latest. In fisheries, MSY is defined as the maximum catch that can be removed from a population over an indefinite period (Maunder, 2008). The MSY target proves specially challenging in mixed Mediterranean fisheries, where more than a hundred commercial species are landed (Lleonart and Maynou, 2003). As each species has specific MSYs, it is extremely difficult to regulate the fishing mortality for each of them independently (Ratz et al., 2007; Mackinson et al., 2009; Guillen et al., 2013), notably when the dynamics of these species may, in turn, be influenced by the environmental (i.e., climate) and fishing impacts (Mueter and Megrey, 2006). Achieving the MSY goal, therefore, is not an easy task because many different contrasting socioeconomic and ecological interests need to be confronted. At the practical level, the main constraints arise when maximizing yields demands socially unacceptable management measures implying drastic reductions of fishing exploitation rates. In order to minimize the negative effect of these measures while balancing the contrasting interests at play, it is essential to work with the active participation of the different actors involved in fisheries assessment and management (scientists, fishermen, and policy-makers).

The EU Regulation also sets out that the objective of sustainable exploitation of marine biological resources is more effectively achieved through a multiannual approach to fisheries management, establishing as a priority multiannual plans (MAPs) reflecting the specificities of different fisheries. The MAPs should be based on scientific, technical, and economic advice and contain conservation measures to restore and maintain fish stocks above the MSY. Wherever possible, the MAPs should cover multiple stocks where those are jointly exploited. The MAPs should also establish the framework for the sustainable exploitation of stocks and marine ecosystems concerned, defining clear time-frames, and safeguard mechanisms for unforeseen developments. The Regulation also states that the MAPs should be adopted in consultation with Advisory Councils, operators in the fishing industry, scientists, and other stakeholders having an interest in fisheries management.

Together with the MSY and MAP approaches, the new CFP contains several other measures (e.g., fish recovery areas, landing obligation, and regionalization), directed to guarantee the ecological and socio-economic sustainability of fisheries. According to all these tenets, the new CFP is moving, in line with the current worldwide global trend (García et al., 2003; Pikitch et al., 2004; Link, 2013), toward the ecosystem approach to fisheries management (EAFM). With this new perspective, the CFP wants to avoid past failures of fisheries management based on monospecific assessment models (Jennings and Rice, 2011; Kvamsdal et al., 2016). Contrary to these models, the EAFM focuses on the need to make trade-offs among environmental, social, and economic objectives explicit to all stakeholders and to better inform decision-making (Jennings and Rice, 2011). Within the current framework of the EAFM, harvest strategies and harvest control rules (HCRs) have become an important tool, increasingly adopted to deal with uncertainty and ecosystem considerations, and to relieve management decisions from short-term political pressure (Kvamsdal et al., 2016). A harvest strategy should specify a process for monitoring and conducting assessments of the biological and economic conditions of the fishery as well as HCRs that control the intensity of fishing activity according to those fishery conditions (Dowling et al., 2008). The introduction of HCRs into modern fisheries management has led to a more complex framework and difficult policy choices, but has substantial benefits such as forcing political decisions to forsake short-term gains for long-term objectives (Deroba and Bence, 2008; Punt, 2010; Kvamsdal et al., 2016). There are different definitions, and even many types and configurations, of HCRs (for reviews, see Deroba and Bence, 2008; Punt, 2010; Kvamsdal et al., 2016). In short, HCRs are explicit guidelines to prevent future stock collapses and allow rebuilding of stocks that are already depleted (Kvamsdal et al., 2016). The success of HCRs is generally enhanced by involvement of stakeholders in the definition of the problem, including assumptions, and co-management (Dichmont et al., 2010). HCRs vary as a result of differences in governance needs and frameworks, but also the unique attributes, histories, and management requirements of each fishery (Kvamsdal et al., 2016). In consequence, the development of harvest strategies with HCRs is strongly related to the main tenets of the new EU CFP such as MAPs, regionalization and MSY target.

The Myfish project (myfishproject.eu/), financed by the EU Seventh Framework Programme, was aimed at analyzing the MSY target and MAP approach contemplated within the new CFP and thus to the delineation of harvest strategies including HCRs. The end result of the project was to construct an operational framework for the implementation of the MSY target as a tool for the future management of European fish stocks. The social dimension formed an integral part of the project whereby the cooperation with relevant stakeholders took place throughout its development to ensure that the management measures proposed were socially acceptable and desirable. The project analyzed five different regional case studies distributed from the Baltic in the north to the Mediterranean in the south. The Mediterranean case study was further split into two different areas, the Balearic Islands and the Aegean Sea in the western and eastern basin, respectively.

The Balearic Islands are one of the most distant insular areas in the Mediterranean, being separated from the Iberian Peninsula by depths of 2,000 m except in the Ibiza Channel (the nearest point between both coastlines) where the maximum depths are 800 m. A comprehensive comparison including different aspects such as geomorphology, habitats, fisheries, and exploitation state of resources and ecosystems between the Balearic Islands and the adjacent coast of the Iberian Peninsula, concluded that the Archipelago should be maintained as an independent unit for assessment and management purposes in the western Mediterranean (Quetglas et al., 2012).

In this paper, we present the regional implementation plan (RIP) for demersal fisheries of the Balearic Islands constructed in the framework of the Myfish project in close collaboration with the most relevant local stakeholders. By definition, the implementation plan constitutes a harvest strategy, including HCRs, aimed at achieving sustainable fisheries in line with Regulation 1380/2013 while balancing contrasting interests (ecosystem, economic, and social). Firstly, the work describes the main fisheries affected by the plan and provides stock assessments to know the exploitation status of the main target species in order to set up the current scenario in the study area. Secondly, alternative management scenarios directed toward maximizing catch and profits while considering societal objectives were evaluated by means of bio-economic models. Thirdly, a set of socially acceptable management measures were provided based on the previous modeling and a constant feed-back with stakeholders. Finally, a monitoring scheme is outlined to assess the progresses of the proposed management actions. The study is intended to be used as a first step toward the definition of MAPs in European fisheries in the study area and a working example of the CFP implementation in the Mediterranean.

METHODS AND RESULTS

The RIP for the Balearic Islands (western Mediterranean) was developed during the 4 years of the Myfish project (2012–2015) in tight collaboration between the scientists working in the project and the main local stakeholders involved in fisheries management: (i) the Fishermen Association; and (ii) the General Directorate of Fisheries of the Government. The collaboration of these two stakeholders included many meetings at local scale, attending different international meetings hold within the project, provision of fisheries data, facilitating cooperation, and feed-back with fishermen and participation in producing all relevant reports, scientific papers, and related material (e.g., DST, see below). The non-governmental organization (NGO) Oceana (oceana.org) published a report entitled *Proposal for a responsible fishing in the Balearic Islands* (Carreras and Cornax, 2011) in the form of five different leaflets including: (i) a global view of the local fisheries; (ii) recreational fisheries; (iii) small-scale fisheries; (iv) marine protected areas; and (v) bottom trawl fisheries. This material has also been analyzed and some proposals included in the RIP, which is therefore underpinned by the four main pillars of fisheries management (Aanesen et al., 2014; Röckmann et al., 2015): scientists, fishermen, policy-makers, and NGOs.

The RIP summarizes the main results of the Myfish project from the Balearic Islands case study. Being the main project aim to provide an operational framework for the implementation of the MSY concept in European waters, the following steps were undertaken to produce the RIP: (i) characterization of the relevant fisheries (fishing tactics, landings, CPUEs); (ii) description of the main fishing grounds; (iii) assessment of the stock status of the target species; (iv) bioeconomic analysis of the main fisheries to maximize economic yields and societal objectives; (v) produce Decision Support Tables (DSTs) as guidelines for managers; (vi) fish price analysis to improve the fisheries profitability; (vii) delineate management proposals to achieve the MSY target; and (viii) establish a monitoring scheme to assess the progresses of the RIP. A brief, general description of the analyses and methodologies used, together with the main results obtained, in all these steps are given below (for further details, see Myfish-RIP-WestMed-EN.pdf). Altogether, this RIP constitutes a harvest strategy for multispecies demersal fisheries from the western Mediterranean with defined objectives, targets, limits (thresholds), and clear management control rules aimed at optimizing socioeconomic and ecological objectives in the framework of Regulation No. 1380/2013.

The present RIP is focused on the main demersal commercial fisheries from the Balearic Islands, the bottom trawl (BTF) and small-scale (SSF) fisheries. The BTF landings account for 59% in terms of biomass and 64% in terms of incomes, while those of the SSF account for 20% in biomass and 27% in incomes. Owing to the importance of recreational fisheries in such an important tourist destination and its interactions with the professional fisheries, general information from available studies on this fishing practice, together with management measures, were also included.

Although the Balearic Islands are constituted by four main islands (Mallorca, Menorca, Ibiza, and Formentera), most of the analyses presented here were done using exclusively data from Mallorca because: (i) the reliability and availability of its fishery statistics is much better than those from the remaining islands; and (ii) its landings represent about 75% of the total Balearics landings.

Fisheries Description

The first step was the characterization of the main fisheries using different time series of fishery statistics provided by the fishermen association, such as landings, CPUEs, and number of vessels. Whereas, data from the BTF was available from previous studies (e.g., Ordines et al., 2006; Palmer et al., 2009; Quetglas et al., 2013), fishing tactics (a combination of target species, gear, and fishing location at a given time of the year; Pelletier and Ferraris, 2000), and fishery statistics from the SSF were determined within Myfish (for methodology, see Quetglas et al., 2016).

In the study area, commercial trawlers use up to four different fishing tactics (Palmer et al., 2009), which are associated with the shallow and deep continental shelf, and the upper and middle continental slope (Guijarro and Massuti, 2006; Ordines et al., 2006). Vessels mainly target striped red mullet (*Mullus surmuletus*) and European hake (*Merluccius merluccius*) on the shallow and deep shelf respectively. However, these two target species are caught along with a large variety of fish and cephalopod species. The Norway lobster (*Nephrops norvegicus*) and the red shrimp (*Aristeus antennatus*) are the main target species on the upper and middle slope respectively. The Norway lobster is caught at the same time as a large number of other fish and crustacean species, but the red shrimp fishery is the only Mediterranean BTF that could be considered monospecific. From 1965, the BTF from Mallorca has showed large variations in the number of vessels, mean engine power and the fishing time at sea (**Figure 1**). The number of trawlers doubled during the first 12 years and reached its maximum of 70 units in 1977,

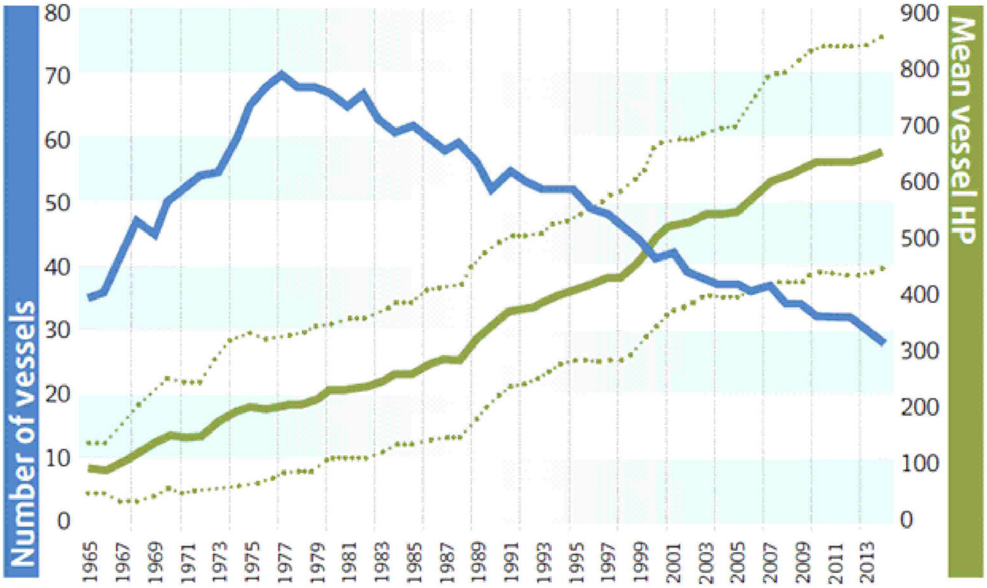


FIGURE 1 | Number of vessels along with its mean and standard deviation of gear power (HP) of the bottom trawl fleet from Mallorca (Balearic Islands) during 1965–2014.

but this number has decreased progressively since then and is currently (2014) lower than the initial number of vessels in 1965 (28 vs. 35).

The SSF targets the following eight fishing tactics and corresponding target species: (i) purse seine: dolphinfish (*Coryphaena hippurus*); (ii) purse seine: transparent goby (*Aphia minuta*); (iii) handline: squid (*Loligo vulgaris*); (iv) trammel net: striped red mullet (*M. surmuletus*); (v) trammel net: cuttlefish (*Sepia officinalis*); (vi) longline: dentex (*Dentex dentex*); (vii) longline: red scorpionfish (*Scorpaena scrofa*); and (viii) trammel net: spiny lobster (*Palinurus elephas*). The fishing tactics targeting dolphinfish, transparent goby, and squid are practically monospecific, having very low by-catches. The remaining fishing tactics, by contrast, yield landings with comparatively important quantities of by-catch species. Altogether, those eight target species have accounted for 52% in terms of landings and 71% in terms of incomes of the SSF. The number of boats has decreased noticeably during the last 25 years in the whole Archipelago, from about 600 units in 1990 down to 254 units in 2013. Currently (2014), the official census of the SSF in the Archipelago includes a total of 340 fishermen and 265 boats. In Mallorca, there are a total of 147 vessels and 202 fishermen.

The decrease observed in the number of vessels in both the BTF and SSF is mainly related to the low attractiveness of fishing to young people, who prefer working on the touristic sector. In spite of such a decrease of fishing units, the fishing capacity has remained relatively constant owing to the concomitant increase of mean engine power (**Figure 1**). In fact, the landings of the main fisheries (BTF, SSF, purse-seine, and pelagic long-line) did not show important fluctuations during the last 15 years and the total landings from the Balearic Islands have not shown any clear trend during the last 75 years (**Figure 2**).

Due to the high number of recreational fishers in the Balearic Islands, its impact on the marine ecosystems and biological resources cannot be ignored. It was estimated that between 5 and 10% of the Archipelago population were recreational fishers (Morales-Nin et al., 2005, 2008). Total annual catches from Mallorca, which included 60 species of fishes and cephalopods, ranged between 1,200 and 2,700 t, accounting for 30–65% of the official commercial landings (4,000 t per year). Based on these figures and the fact that recreational fishing shares with the SSF some of its main target species, it is essential to incorporate information on catches of this fleet when assessing and managing fishery resources from the Balearic Islands.

Demersal Fishing Grounds

The fishing grounds exploited by the demersal fisheries from the Balearic Islands are characterized by the presence of sensitive (SH) and essential fish (EFH) habitats, especially on the coastal continental shelf. The fishing grounds traditionally exploited by the BTF overlap with red algae beds including maërl and *Peyssonnelia* beds (Ordines and Massuti, 2009), which are considered a SH (protected under European fishing regulation EC No 1967/2006 of 21 December 2006) and an EFH (Ordines et al., 2015), respectively. The crinoid beds, also considered an EFH (Colloca et al., 2004; Ardizzone, 2006), dominate certain areas of the deep shelf, primarily between 120 and 200 m depth. Studies carried out in the Balearic Islands confirm the importance of these habitats in structuring demersal resources assemblages (Ordines and Massuti, 2009; Ordines et al., 2009). These studies have shown that benthic biogenic habitats such as maërl and *Peyssonnelia* beds not only affect the distribution of demersal resources, but also favors its individual physiological condition, allowing them to afford critical life stages such as

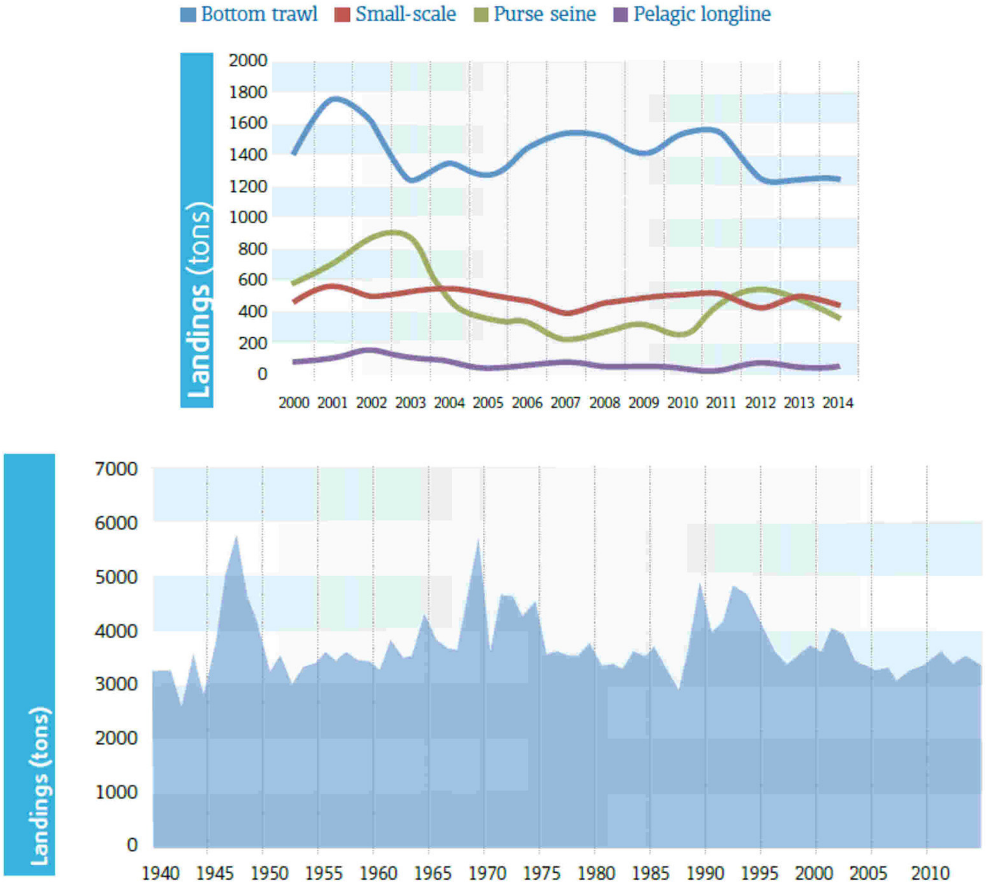


FIGURE 2 | Landings of the main fishing fleets from Mallorca between 2000 and 2014 (above) and total landings from the Balearic Islands during the last 75 years (below).

reproduction with more lipid reserves than individuals living in bare sandy bottoms (Ordines et al., 2011, 2015). These habitats constitute "living bottom structures" that enhance the three-dimensional complexity of benthic communities and its productivity, providing refuge for small-sized species and juvenile individuals of important fishing resources (Ordines et al., 2009).

The presence of these benthic habitats highlights the need to go toward multispecies and ecosystem-based assessment and management of demersal fisheries in the Balearic Islands. Thus, fishery management on the continental shelf requires the development of technical measures to protect benthic communities, which could also benefit demersal resources populations by reducing the direct impact of fishing mortality on crucial life stages (juveniles and spawners) and the indirect impact of fishing represented by the loss of SH and EFH.

Stock Status

The exploitation state of the BTF target species was available from stock assessments carried out by some of the authors in the framework of different STECF and GFCM working groups. As there was not available information on the stock status of the target species of the SSF, they were assessed with surplus production models using the ASPIC software (Prager, 2004). For details on the assessment methods used, see references in **Table 1**.

Table 1 compiles the total number of BTF stocks from the Balearic Islands assessed up to now, highlighting the four main target species. Hake shows the worst stock status, with current fishing mortality (F_c) being more than seven times the biological reference point ($F_{0.1}$). The MSY for striped red mullet, hake, Norway lobster, and red shrimp stocks would be achieved with effort reductions of 23, 71, 26, and 40%, respectively (Merino et al., 2015).

Surplus production models were used to assess the eight target species of the SSF (**Table 1**) with the exception of the dolphinfish. The highly migratory behavior of this species prevents the use of stock assessment methods at local scales such as in our case (STECF, 2013), whereby the exploitation status of dolphinfish was not assessed. Except striped red mullet and squid, all other stocks are currently overexploited and the MSY would be achieved with the following effort reductions (Quetglas et al., 2016): spiny lobster (53%), red scorpionfish (51%), dentex (50%), transparent goby (35%), and cuttlefish (21%).

TABLE 1 | Stock status indicators of demersal species taken by the bottom trawl (BTF) and small-scale (SSF) fisheries from the Balearic Islands showing the current fishing mortality (F_C), the reference biological point (F_{RP}: $F_{0.1}$ for BTF, F_{MSY} for SSF), the ratio between them (F_C/F_{RP}), and the information source.

Fishery	Stock	Fc	F_{RP}	Fc/F_{RP}	Sources
BTF	Black-bellied angler	0.84	0.08	10.5	STECF, 2014
	European hake	1.15	0.15	7.7	GFCM, 2014
	Red mullet	0.93	0.15	6.2	GFCM, 2014
	Striped red mullet	0.51	0.17	3.0	GFCM, 2014
	Red shrimp	0.42	0.24	1.7	GFCM, 2014
	Norway lobster	0.29	0.17	1.7	STECF, 2014
	Common octopus	0.47	0.32	1.5	STECF, 2012
	Deep-water pink shrimp	0.77	0.62	1.2	STECF, 2013
	Cuttlefish	0.44	0.41	1.1	Quetglas et al., 2015
SSF	*Dentex*	0.26	0.13	2.0	Quetglas et al., 2016
	Red scorpionfish	0.32	0.16	2.0	
	Striped red mullet	0.10	0.14	0.7	
	Transparent goby	0.13	0.08	1.5	
	Spiny lobster	0.31	0.15	2.1	
	Cuttlefish	0.18	0.14	1.3	
	Squid	0.16	0.16	1.0	

Target species are in italics.

Bioeconomic Analysis

In order to achieve conservation and economic objectives, deciding the correct dimension of fisheries, and their activity is paramount. For this purpose, the impact on fisheries performance indicators of the following four management scenarios were tested for the BTF and SSF: (i) a projection of current conditions (Control); (ii) the main target species will be located in the green quadrant of a Kobe plot, that is $F < F_{MSY}$ and $B > B_{MSY}$ (All Green, AG); (iii) the maximum aggregated catch (Multispecies Maximum Sustainable Yield, MMSY) of the target species will be sought; and (iv) the Maximum Economic Yield (MEY) of the fishery will be achieved. The bioeconomic analyses were carried out using the MEFISTO 3.0 bio-economic simulation model (Mediterranean Fisheries Simulation Tools, www.mefisto.info), which was specifically designed to address management issues under the Mediterranean regulation system (Lleonart et al., 2003). For details on the bioeconomic analyses, see Merino et al. (2015) and Quetglas et al. (2016) for the BTF and SSF, respectively.

In order to reach the AG scenario (all four target species would be exploited below their MSY) current fishing effort of trawlers from Mallorca would have to be reduced by 71%; with this scenario, hake would be at B_{MSY} and the biomass of striped red shrimp, red mullet, and Norway lobster would be above 1.5 times the B_{MSY}. To achieve the MMSY scenario, the activity of trawlers would have to be reduced by 57%; under these conditions, hake would continue to be overexploited but at more secure levels than in the Control scenario. Currently, the BTF from Mallorca generates €1.29 million of net profits. In order to achieve the MEY, which the model situates at €1.90 million, the fishing effort has to be reduced by 48% (∼115.44 fishing days per year). Under this scenario, hake would continue to be overexploited while the other three species would remain at secure levels, with red shrimp very close to full exploitation. Lower, moderate reductions of fishing effort such as reducing from 5 to 4 working days per week, would also bring notable profit increases (>€1.60 million).

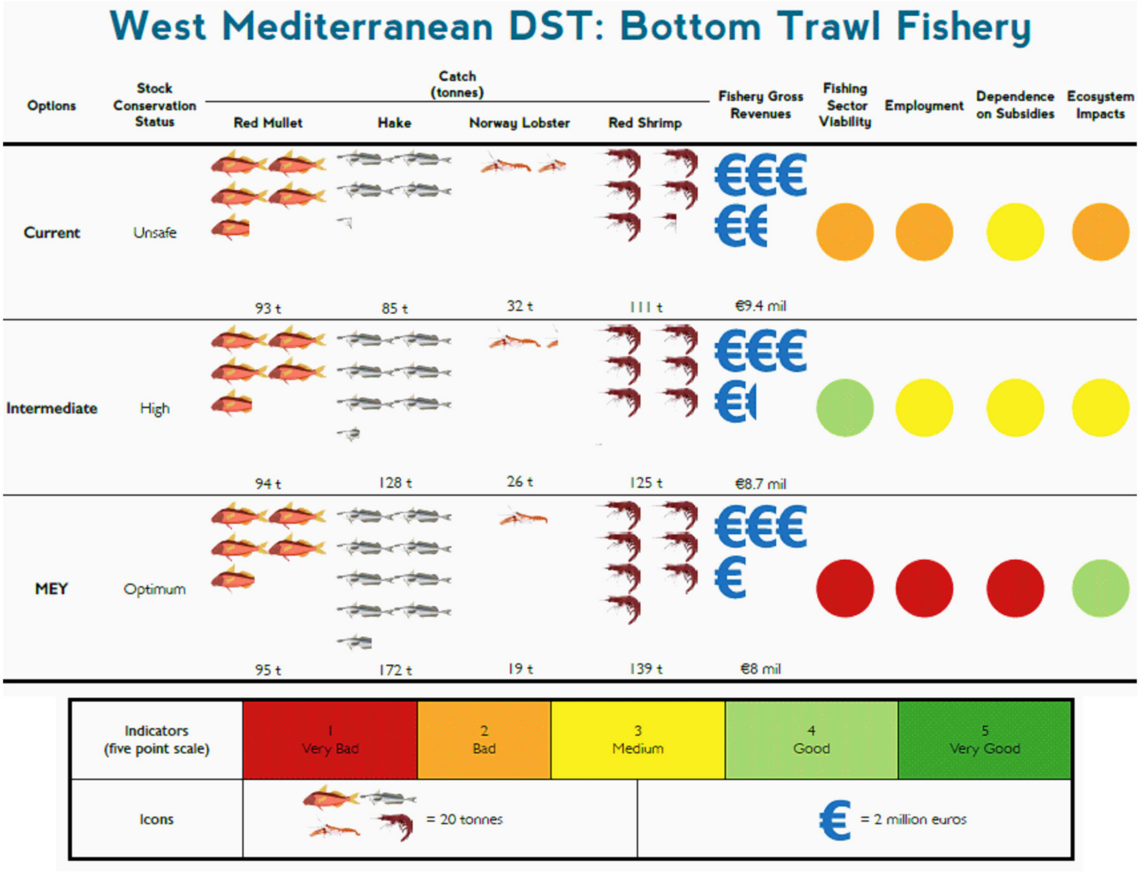
The effort reductions required to achieve sustainable exploitation of the SSF are much lower than those foreseen for the BTF. According to the bioeconomic model results, if all seven target species of the SSF were exploited below their MSY (AG scenario), current fishing effort would have to be reduced by 53%. If the aggregated catch from all species was to be maximized (MMSY), the activity of the SSF would have to be reduced by 38%. In case the maximum economic yield (MEY) would have to be attained, reductions required in fishing effort would be markedly lower (28%). Under current economic conditions and current fishing effort, the SSF generates €2.86 million of net profits. With the parameters used in our modeling, total profits would slightly decrease down to €2.82 million in the AG scenario and would reach as much as about €3.3 million under the MMSY (€3.29 million) and MEY (€3.34 million) scenarios. The AG scenario would lead all stocks to the bottom-right area, where dentex, scorpionfish, and spiny lobster would be at B_{MSY} while the biomass of the remaining stocks would range between 1.3 and 1.7 times the B_{MSY}. Under the MMSY and MEY scenarios, three stocks (dentex, scorpionfish, and lobster) would continue to be overexploited but at more secure levels than in the control scenario.

Decision Support Tables

The main results of the aforementioned bioeconomic analyses are the basis of DSTs, graphical tables that reflect the effects and trade-offs of implementing different MSY options on ecosystem, economic, and social constraints and with particular focus on the risk of exceeding acceptable levels for these constraints. The DSTs have been designed to convey complex, alternative management scenarios in a simple and understandable way to support fisheries managers in their decision making. There were constant feed-back and several meetings with local stakeholders to outline and design the DSTs.

The DSTs were prepared for the BTF and SSF separately and include three different management scenarios (**Figures 3**, **4**): (i) the current situation, which is considered unsustainable given that all (BTF) or most (SSF) stocks are over-exploited; (ii) the MEY scenario predicted by the bio-economic model, which was considered unfeasible by the fishermen owing to the very high reductions in fishing effort required; and (iii) an intermediate scenario in between these two previous, extreme situations in which the figures (effort, catch, economic value) are the average between the current and the predicted MEY scenarios.

The management scenario agreed with stakeholders includes the reductions of fishing effort necessary to obtain the catches shown in the intermediate scenario. The benefits of such fishing effort reductions would be two-fold. Firstly, an improvement in the exploitation status of the different target stocks and hence on the demersal ecosystems exploited by the BTF and SSF. Secondly, an improvement in the viability of the fishing



West Mediterranean DST: Bottom Trawl Fishery

Options	Stock Conservation Status	Catch (tonnes) Red Mullet	Catch (tonnes) Hake	Catch (tonnes) Norway Lobster	Catch (tonnes) Red Shrimp	Fishery Gross Revenues	Fishing Sector Viability	Employment	Dependence on Subsidies	Ecosystem Impacts
Current	Unsafe	93 t	85 t	32 t	111 t	€€€€€ €9.4 mil	🟠	🟠	🟡	🟠
Intermediate	High	94 t	128 t	26 t	125 t	€€€€ €8.7 mil	🟢	🟡	🟡	🟡
MEY	Optimum	95 t	172 t	19 t	139 t	€€€€ €8 mil	🔴	🔴	🔴	🟢

Indicators (five point scale)	1 Very Bad	2 Bad	3 Medium	4 Good	5 Very Good
Icons	= 20 tonnes			€ = 2 million euros	

FIGURE 3 | Visualized form of the Decision Support Table from the bottom trawl fishery.

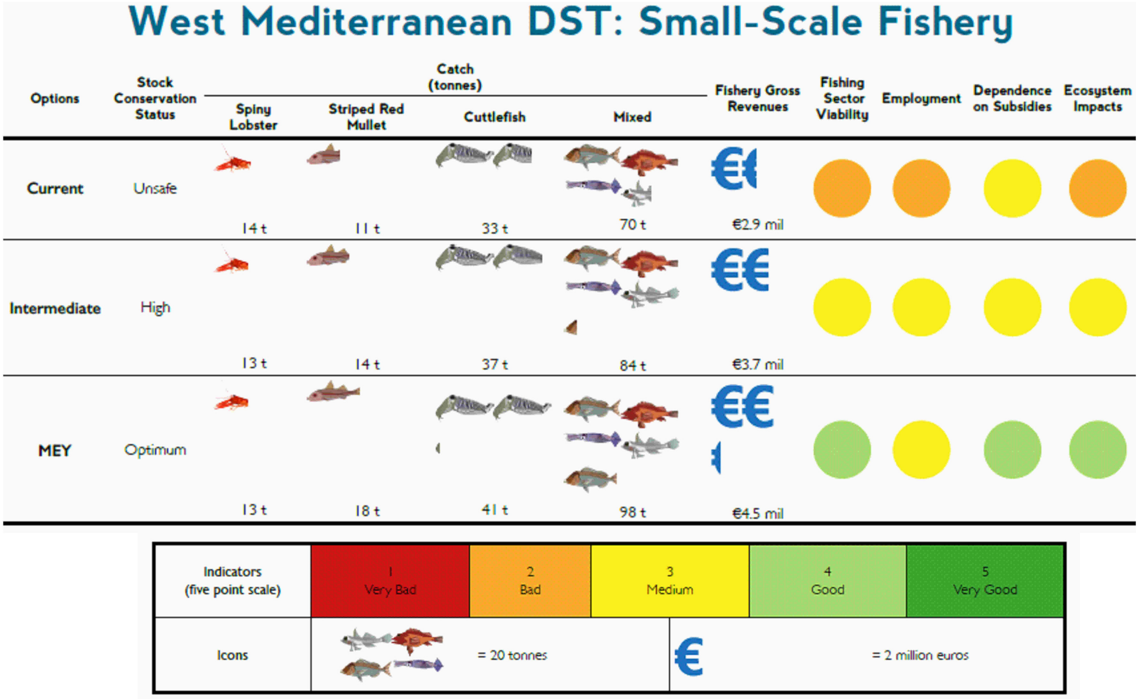
industry, primarily by means of reducing fishing costs in terms of substantial reductions in fuel consumption.

Fish Price Analysis

Together with the increase on fuel price, Mallorca fishermen, as elsewhere in the Mediterranean, have to cope with a constant decrease of the fish price (due to strong market competence with imported seafood) which jeopardizes its economic viability. According to stakeholders, the viability of the fishery in the Balearic Islands depends on marketing aspects (increasing fish/fuel price ratio) rather than on the exploitation status of the main stocks. Consequently, marketing improvements in the fishing industry should be done in order to increase the economic value of the main species. In order to investigate improvements on the commercialization scheme, price formation in the BTF and SSF were analyzed using a 15 years' database (2000–2014) of daily sale bills providing catches and prices per day and vessel. Factors influencing the price formation were estimated using hedonic analysis, which specifies a product price as a function of different attributes.

The average price of fish landed by the BTF at the Mallorca auction was 6.1€/kg, with a peak of 7.3€/kg in 2005 followed by a gradual decrease since then down to the current 6.4€/kg (a 12% drop measured in nominal prices and 26% if constant 2014 price are considered). On the other hand, the fuel price increased a 45% along the same period, causing a constant decrease of the fish/fuel price ratio. Compared to the BTF, fish prices from the SSF are in general higher (7.1€/kg average fish price) and do not suffer important reductions; the average fish price peaked at 9.5€/kg in 2007 and has slightly decreased since then down to the current 9.1€/kg (only a 4% drop measured in nominal prices). Owing to its high commercial interest, red shrimp is the best option to implement new commercialization strategies for the BTF. Sales of red shrimp represent 40% of the total income from the BTF and 70% of the incomes coming from the four main target species.

Size was the most important factor affecting seafood prices, especially in the BTF where the prizes of small-sized individuals of red shrimp and Norway lobster are 71 and 66% lower than the prices fetched by the largest commercial category. Therefore, improving the BTF selectivity would be efficient in terms of enhancing fleet's revenues and profitability. The day of the week is also important (lowest prices in Tuesdays, highest prices in Fridays–Saturdays), whereby reducing the fishing days per week as a management measure should target those days with lower prices to minimize losses. The season is also relevant, with luxury



West Mediterranean DST: Small-Scale Fishery

Options	Stock Conservation Status	Catch (tonnes)				Fishery Gross Revenues	Fishing Sector Viability	Employment	Dependence on Subsidies	Ecosystem Impacts
		Spiny Lobster	Striped Red Mullet	Cuttlefish	Mixed					
Current	Unsafe	14 t	11 t	33 t	70 t	€2.9 mil	🟠	🟠	🟡	🟠
Intermediate	High	13 t	14 t	37 t	84 t	€3.7 mil	🟡	🟡	🟡	🟡
MEY	Optimum	13 t	18 t	41 t	98 t	€4.5 mil	🟢	🟡	🟢	🟢

Indicators (five point scale)	1 Very Bad	2 Bad	3 Medium	4 Good	5 Very Good
Icons	= 20 tonnes		€ = 2 million euros		

FIGURE 4 | Visualized form of the Decision Support Table from the small-scale fishery.

products such as red shrimp or lobsters presenting high peaks during Christmas and summer periods.

Management Proposals

A set of management proposals were outlined based on the main results obtained in all previous analyses, together with discussions hold with representatives of the two main local stakeholders during the 4 years of the project development. As aforementioned, management proposals from the NGO Oceana were also reviewed from the available literature (Carreras and Cornax, 2011). Proposals for both the commercial and recreational fisheries were included (**Figure 5**). The management actions proposed to improve the status of the exploited stocks and the commercialization of fish were split into the two following sections: (i) exploitation model; and (ii) business model.

Commercial Fisheries

Exploitation model

The main objective in this point is to optimize the fishing effort by means of reducing the fishing activity and using more selective gears.

General management actions.

Measures under this section apply indistinctly to both commercial fisheries, the BTF, and SSF.

(A) Compliance of current fishery regulations
An effective management should begin with a full compliance of fishery regulations. Consequently, efforts should be put to ensure this compliance from the scratch and a continuous surveillance established to ensure its fulfillment with time. Not doing it might prevent the success of further management measures.

(B) Fishing effort reductions
Owing to the sharp decrease in the number of fishing units in both fisheries, further reductions are not contemplated in order to ensure the viability of the fishing industry. If the decreasing rate observed in the BTF from Mallorca during the last 25 years is maintained, the fleet would disappear in less than 25 years (**Figure 6**). As explained below, the actions intended to reduce the fishing effort will include, for instance, reducing the time at sea.

(C) Review and update the minimum landing size (MLS) for some species
In the Mediterranean, the current landing obligation (Article 15 of CFP) only applies to a reduced list of species having MLS. To ensure the sustainability of the fishing exploitation, those MLS should be equal, or higher than, the size at first maturity (L_{50}). As L_{50} is the size at which the 50% of the population has reached the sexual maturity, this measure will allow that about half of the population of commercial species can reach reproduction at least once. Paradoxically, this is not the case in many stocks in the Mediterranean.

(D) Conservation of essential fish habitats
These measures could be based on spatial (and/or temporal) closures in addition to the already existing net of marine protected areas in the Balearic Islands. Areas and periods of especial interest for hatching and recruitment of the main commercial species should be avoided by fishermen,

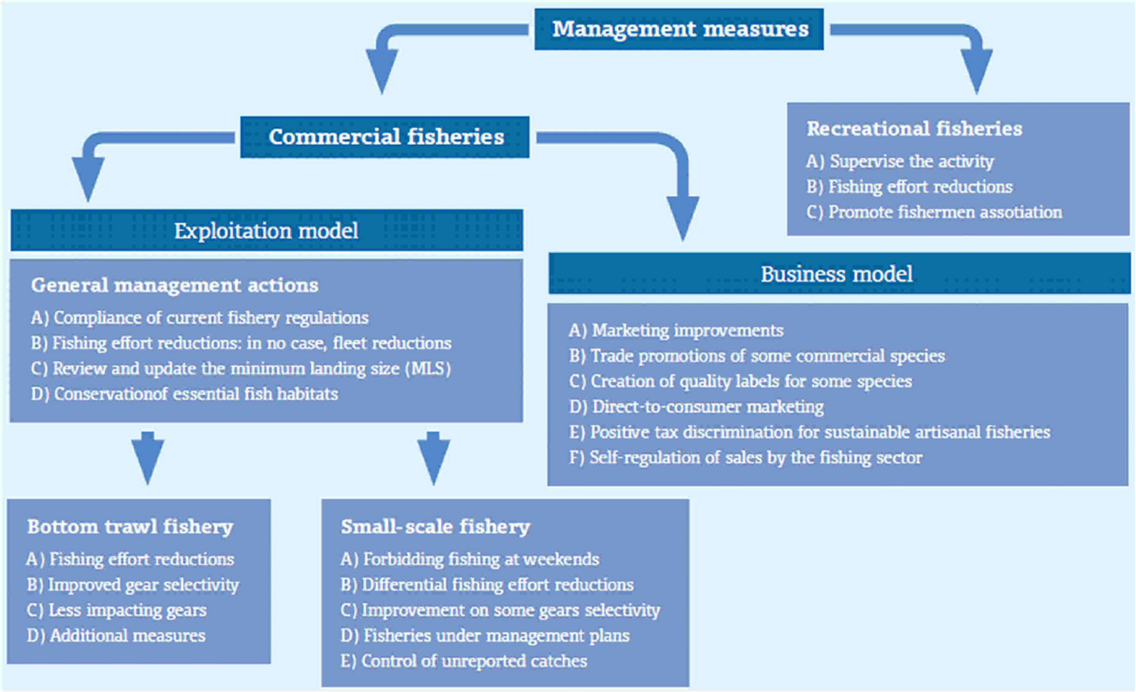


FIGURE 5 | Scheme of the management measures proposed in this study for the demersal fisheries from the Balearic Islands (western Mediterranean).

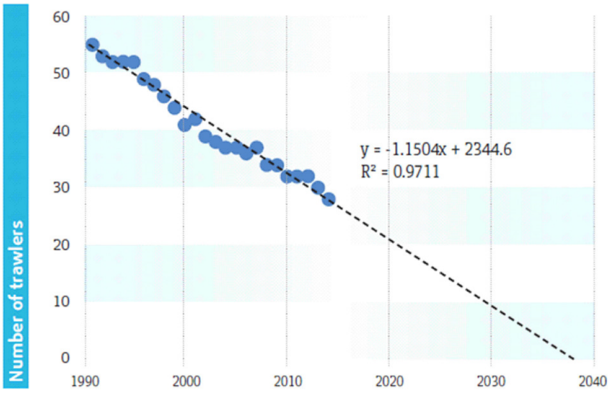


FIGURE 6 | Number of bottom trawlers in Mallorca during the last 25 years with the corresponding linear regression fit and its extrapolation until the fleet disappearance (2038).

preferentially by those using less selective gears such as the BTF. Such avoidance should be based on scientific studies, complemented with fishermen knowledge, to map the spatiotemporal distribution of fish and hatching and nursery areas.

Bottom trawl fishery.

(A) Fishing effort reductions
Fishing effort reductions should be based on reducing time at sea, either in terms of hours per day or days per week. Moving from the current 5 days per week to 4 would imply not only reducing the fishing effort by 20% but also reducing the exploitation costs, primarily due to fuel saving. In experiences undertaken in Alicante, results showed that the losses from banning on Wednesday might be compensated by price increases and reductions of exploitation costs (Samy-Kamal et al., 2015). In case the reductions of fishing effort were not applied in terms of days per week, an alternative option could be decreasing the total number of working hours per day.

Given that bottom trawlers operate on different bathymetric strata depending on the target species, differential effort reductions should be put in practice according to the exploitation status of each single stock (**Table 1**). This would not imply stopping the fishing activity, but a sort of diversification of the fishing exploitation to focus on healthier stocks until the recovery of the most impacted ones.

(B) Improved gear selectivity
According to recent studies (Colloca et al., 2013; Vasilakopoulos et al., 2014), improvements in the fisheries selectivity would be more effective than reducing the fishing effort in order to manage Mediterranean BTFs. Although the recent change in mesh geometry (Council Regulation No. 1967/2006) improved the gear selectivity, it was not effective for important by-catch resources whereby additional technical improvements are still needed (e.g., square mesh panels and sorting grids).

(C) Less impacting gears
Technical modifications to reduce the physical impact of BTF gears on the seabed are needed. The use of mid-water doors, shorter sweeps, and lighter nets has proved successful, since these modifications allowed obtaining similar catches than those obtained with traditional gears but with a significant reduction of fuel consumption (Guijarro et al., submitted). Consequently, these modifications contribute to improve not only the ecological fingerprint through lower physical impact and lower CO_2 emissions, but also the economic efficiency of the BTF.

(D) Additional measures
According to Oceana (Carreras and Cornax, 2011), the bottom trawl fishing on continental shelf grounds should be forbidden in the Balearic Islands because it is an ecologically (high physical impact on the bottom and high discard rates) and economically (low commercial value of catches and high fuel consumption) unsustainable fishery. To our view, however, this would not be a good measure. Firstly, it would concentrate the fishing activity to slope grounds where the main target species are Norway lobster and red shrimp, increasing the fishing effort over resources that are already in an overexploitation status. Secondly, the absence of fishing resources from the continental shelf grounds in the market chain would make difficult the maintenance of the marketing of local, fresh seafood products from the Balearic Islands.

Small-scale fishery.

(A) Forbidding fishing at weekends
Under current regulations, the SSF is allowed to fish from Monday to Saturday. Catches taken on Saturday, however, cannot be commercialized until next Tuesday whereby they are alternatively sold to consumers directly. To avoid this commercialization problem, together with reducing the fishing exploitation of the SSF, fishing might be forbidden during the weekends, reducing the weekly fishing activity from Monday to Friday. According to the Fishery Association of the Balearic Islands, preliminary experiences with different fisheries (e.g., dolphinfish, picarel, and transparent goby) have proved to be positive, both for the resource and its commercialization.

(B) Differential fishing effort reductions
As in the case of the BTF, differential fishing effort reductions might be implemented for the SSF since this fleet operates on different target species with contrasting exploitation states (**Table 1**). As above, this would not imply stopping the fishing activity, but a sort of diversification of the fishing exploitation to focus on healthier stocks until the recovery of the most impacted ones.

(C) Improvements on some gears selectivity
Recent studies carried out in the Balearic Islands (Goñi et al., 2013) demonstrate that the selectivity of the SSF can also be improved. These studies focused on the trammel net fishery targeting the spiny lobster and showed that using experimental nets of polyethylene multi-monofilament, instead of the traditional ones of polyamide multifilament, reduced both the number of lobsters below the MLS and the discards of rodoliths. Further improvements such as replacing the trammel net by gillnet, increasing the mesh size, or reducing the soaking time should also be investigated.

(D) Tagging catches
Recent studies in the Archipelago have demonstrated the feasibility of using V-notch marks on the tail flipper of breeding female spiny lobsters (Goñi et al., 2013). These marks are successfully used in other decapod crustacean fisheries such as in the North Atlantic to identify individuals under the legal size and breeding females (Telsnig, 2013) and in the Western Australia to avoid the commercialization of recreational catches (Acheson and Gardner, 2011). The results obtained so far with lobsters suggest that V-notch marks would be an effective measure to protect breeding females returned at sea, thus increasing the reproductive potential of the population.

(E) Fisheries under management plans
Some SSF, such as the transparent goby, are already integrated under management plans. According to the Fisheries Association, integrating all SSF under management plans will be highly beneficial to improve not only the exploitation state of the main target species but also its marketing and commercialization. For this purpose, management plans have to be associated with quality labels (ecolabels) for the main target stocks, which should be a guaranty of seafood obtained through sustainable exploitation.

(F) Control of unreported catches
Sale of fish outside the official market is an important issue in SSF (25% of the reported catch; Carreras et al., 2015), especially in species with high commercial value such as dentex, red scorpionfish, and spiny lobster. Together with its effects on commercialization, unreported catches are highly detrimental for the assessment and management of SSF. This reinforces the need to sensitize the fishing sector about the importance of providing scientists the best data possible in order to help improving the stock assessment and management.

Business model

The main objectives here are achieving reductions in exploitation costs, primarily fuel consumption, together with increases in revenues by means of marketing actions. It should be noted that the measures listed in the previous section will help addressing those objectives, since most of them entail fuel savings due to reductions of fishing activity and fish price increases as a result of lower supply. Although this issue demands specialized socio-economic studies, some general actions are listed below.

(A) Marketing improvements
In order to increase the prices of some species, especially those with the highest commercial value, marketing campaigns should be launched. As aforementioned, red shrimp is the best option to implement new

commercialization strategies for the BTF. However, there are many other examples from the SSF since it catches different species of fish (e.g., grouper, John Dory) and crustaceans (e.g., spiny lobster) of high commercial value.

(B) Trade promotions of some commercial species
The globalization of trade markets has changed consumer habits and affected seriously the commercialization of fresh Mediterranean seafood. This calls for trade promotions to potentiate local products, either by recovering the now abandoned traditional consumption of some species such as the picarel (*Spicara smaris*) or promoting other by-catch species both at home and at restaurants.

(C) Creation of quality labels for some species
Today, there is an increasing number of markets demanding quality labels or ecolabeled products (e.g., Marine Stewardship Council-MSC). For many consumers, the quality and freshness of seafood, and even the environmental credibility, plays an increasing role in purchasing decisions. In a highly touristic place such as the Balearic Islands, this formula should be enhanced, especially for high-valued species such as spiny lobster, John Dory, or red scorpionfish.

(D) Direct-to-consumer marketing
Direct marketing in the Balearic Islands may have several advantages: (i) higher incomes to fishermen by avoiding unnecessary retailers; (ii) lower transportation costs since the fish will not be sent to the central auction wharf in Palma; (iii) fresher fish, which might imply higher prices, as a result of reducing the market chain. Direct marketing, however, should be accompanied with a reliable control system in order to avoid black market and unreported catches.

(E) Positive tax discrimination for sustainable artisanal fisheries
This measure would be directed to favor artisanal fisheries, primarily those using more selective gears such as traps, in front of more impacting fisheries such as bottom trawl. The use of traps in some specific fisheries, such as the spiny lobster fishery, was a common practice in the Balearic Islands some time ago, but it was completely abandoned during the early 2000s for more impacting, profitable gears such as trammel nets.

(F) Self-regulation of sales by the fishing sector
At the fishing industry own initiative, this measure is already in place for some SSF, such as dolphinfish in the whole Mallorca and spiny lobster in some specific ports. Setting daily quotas for dolphinfish and both seasonal quotas and a constant mean price in the case of spiny lobster is intended to render higher economic yields to fishermen. This measure could then be extended to other target species, either belonging to the BTF or the SSF.

Recreational Fishery

(A) Supervise the activity
Currently there is not an official record of catches from the recreational fishery in the Balearic Islands. However, the importance of this fishing practice makes essential incorporating these catches when assessing and managing the fishery resources from the Archipelago. It is also necessary to improve the supervision of the activity at sea in order to ensure the compliance of current regulations, together with controlling the final destination of the catches as they cannot be commercialized in any case.

(B) Fishing effort reductions
The effort reductions necessary to ensure a sustainable management of marine resources cannot fall exclusively on the professional sector, but should also apply to the recreational fishery. Fishing effort limitations could be carried out through reductions in the number of allowed fishing days and the maximum authorized catches in order to adapt them to the increasing number of practitioners in recent decades (there are about 70 recreational fishers for every professional fisherman). Currently there is no limitation of activity, except for temporary closures for some species (*Xyrichthys novacula* and *Seriola dumerili*). The fishing effort could also be reduced by activity limitations in certain areas, such as the marine reserves where, furthermore, the spearfishing should be completely banned. In the case of spearfishing, the prohibition of using artificial light would increase the chances of survival of fish seeking refuge as a defense strategy.

(C) Promote fishermen associations
Recreational fishermen associations would facilitate the collaboration and involvement of the sector in the management of this fishing activity, especially in providing information about their catches.

Monitoring

Once the management measures are put into force, a monitoring plan should be established in order to assess the effects of those measures and the actions to be undertaken if the expected results (improved exploitation status of target stocks) are not achieved. As aforementioned, an effective management should begin with a full compliance of fishery regulations. Consequently, an effective and reliable control system should be set up to ensure fishermen compliance with both the fishery regulations and the management actions contemplated within this RIP.

A scientific surveillance system to monitor the effects of the management measures is also needed. Such a scientific monitoring would use different sampling and data sources to assess the RIP progresses, primarily the exploitation state of the main target species. Currently, this monitoring in European waters is implemented through the Data Collection Framework (DCF, datacollection.jrc.ec.europa.eu/), whereby the member states collect, manage, and make available a wide range of fisheries data needed for scientific advice. This data collection encompasses:

(i) Fishery-dependent data: it includes time series of landings and fishing effort obtained from fishery statistics, along with scientific sampling at fish markets or on board commercial vessels to analyse the catch species composition and the size structure of the main target stocks. The availability of these data sources fully depends on the collaboration of the fishing sector (Guijarro et al., 2012a).

(ii) Fishery-independent data: it refers to scientific sampling on board research vessels. From 1994 on, the EU and the participating member states are co-financing the MEDITS (MEDIterranean Trawl Surveys) programme. This programme aims to conduct coordinated scientific bottom trawl surveys in the Mediterranean European waters, covering trawlable grounds over the shelf and upper slope from 10 to 800 m depth (Bertrand et al., 2002). Scientific surveys following the MEDITS protocol started in the Balearic Islands in 2001, being included in the MEDITS programme in 2007. Since then the fishing grounds (50–800 m) around Mallorca and Menorca are surveyed annually during late spring or early summer. The data collected in these surveys allows assessing the health of the ecosystems and living resources from the Balearic Islands using information independent from the fishing activity.

Using all these information sources, the surveillance system will assess the exploitation estate of the main target stocks (**Table 1**) and present the results to the suitable international forums, the GFCM, and STECF.

Conservation reference points consistent with the objective of achieving the MSY target by 2020 will be set out for all assessed stocks. Fishing mortality (F) and biomass (B) relative to those foreseen under the MSY will be used: F/F_{MSY} and B/B_{MSY} respectively. As a general consensus, stocks with $B/B_{MSY} < 1$ and $F/F_{MSY} > 1$ are indicative of an overexploitation state, while $B/B_{MSY} > 1$ and $F/F_{MSY} < 1$ are indicative of an underexploitation state. Given that the main objective is to exploit the target stocks at MSY, corrective measures will be applied in case the assessments reveal overexploited stocks.

In order to assess not only the main target stocks but also other species or taxonomic groups, together with different ecosystem compartments, additional conservation indicators will be used. This assessment will allow revealing population trends in both commercial (by-catches) and non-commercial (discards) species and also taxonomic groups with special sensitivity to fishing exploitation such as elasmobranchs (Quetglas et al., 2016). To this end, conservation indicators agreed within the Marine Strategy Framework Directive (MSFD), which aims to achieve Good Environmental Status (GES) of the EU's marine waters by 2020 and to protect the resource base upon which marine-related economic and social activities depend, will be monitored. The preliminary assessment of the Balearic Islands area under the MSFD is currently available (MSFD-Levantino Balear) and will be monitored in the future according to the MSFD road map.

Assessing the complexity of exploited ecosystems using a variety of indicators demands the use of summarizing approaches such as the traffic lights methodology, which has already been used in the Balearic Islands (Guijarro et al., 2011, 2012b). This approach was firstly proposed as a type of precautionary management framework suitable for use in fishery assessment in data-poor situations (Caddy, 2002), but it can also be used to assess the status of all stocks whether rich or poor in data (Halliday et al., 2001). It has been applied for single- and multi-species assessments both in the Atlantic and the Mediterranean (e.g., Caddy et al., 2005; Ceriola et al., 2007) and appears to be more precautionary than traditional stock assessment methods (Koeller et al., 2000). As above, if this approach reveals negative trends in population or ecosystem indicators, corrective measures will be designed.

DISCUSSION

Recent reviews have revealed the serious overfishing of most Mediterranean stocks (Colloca et al., 2013; European Commission, 2014; Vasilakopoulos et al., 2014), which is in contrast with the improvement observed in other European areas (European Commission, 2014). The reasons for such a contrasting situation probably lay in the governance systems of these regions rather than in the nature of their resources (Smith and Garcia, 2014). Fisheries management in the Mediterranean has been ineffective, necessitating urgent reforms of the management measures aiming to guarantee the sustainability of resources. This reform should not only focus on reducing the exploitation rate and on improving selectivity (Colloca et al., 2013; Vasilakopoulos et al., 2014) but also on the political and socioeconomic changes beyond fishery management (Smith and Garcia, 2014). The new EU CFP constitutes an excellent opportunity to introduce the changes needed for such a reform, as it has as a main objective ensuring that fishing activities are environmentally sustainable in the long-term by means of the implementation of the EAFM. This approach demands the development of management strategies for the entire social and ecological system, where humans are a fundamental part of the ecosystem (Ramirez-Monsalve et al., 2016). Managing human activities should be organized at the appropriate geopolitical level matching the scale of the ecosystem, hence organizing marine management at the regional level (van Hoof, 2015). Harvest strategies, including HCRs, lie at the heart of these management developments, and can facilitate a fisheries governance system where regulators and fishers work together to decide on overall harvest (Kvamsdal et al., 2016).

In this paper, we outlined a harvest strategy for the multispecific demersal fisheries from the Balearic Islands (western Mediterranean) aimed at optimizing socioeconomic and ecosystem objectives in the framework of Regulation N° 1380/2013. This harvest strategy is therefore focused on the general objective of the new CFP to achieve the sustainable exploitation of marine living resources establishing multiannual plans under the regionalization principle.

To our view, the most urgent measure for fisheries management in the Mediterranean should be a clear determination of law enforcement by riparian countries, which would probably do unnecessary implementing new, more restrictive regulations than the currently existing ones. It is a non-sense setting fishing regulations if its fulfillment will not be controlled, as occurs, for instance, with the limitation of maximum gear power for bottom trawlers, the maximum length of nets for the small-scale fishery, and the conservation of maërl grounds.

The Mediterranean context (multispecies, multifleet) demands specific, bespoke measures suited to differences in the exploitation state, not only among the main stocks but also among different regions (regionalization principle). Managing human activities should be organized at the appropriate geopolitical level matching the scale of the ecosystem, hence organizing marine management at the regional level (van Hoof, 2015). Differential effort reductions in line with the status of each single stock should be used (**Table 1**), with the fishing exploitation focusing on healthier stocks until the recovery of the most impacted ones. Owing to its high overexploitation, stronger measures should be enforced for hake and even a recovery plan might be considered. In addition, the ecosystem-based fisheries management must integrate not only the main target stocks, but also relevant by-catch species (Ordines et al., 2014) and take into account the conservation of the habitats present on the fishing grounds (Ordines et al., 2015).

In the Balearic Islands (GSA05), the fishing effort has remained relatively low as compared to that in the nearby areas (Quetglas et al., 2012). The all-time maximum number of bottom trawlers in Mallorca, for instance, has been 70 units in 1977 and presently (2014) there are only 28 trawlers and some vessels leave the fishery every year. These values are clearly very far from the total number of vessels in GSA06, the adjacent area of the Iberian Peninsula where even some individual ports have more trawlers than all the ports of Mallorca combined. Trawl fishing exploitation in GSA05 is much lower than in GSA06, with the density of trawlers around the Balearic Islands being one order of magnitude lower than in adjacent waters (Massutí and Guijarro, 2004). As a result, the demersal resources and ecosystems in GSA05 are in a healthier state than in GSA06, which is reflected in Quetglas et al. (2012), Ordines (2015): (i) the size-structure of the main commercial stocks; (ii) the higher abundance and diversity of vulnerable species such as elasmobranchs; and (iii) the presence of some sensitive benthic habitats, some of them acting as essential fish habitats, which overlap with traditional fishing grounds. These differences among areas should be taken into account for fisheries management, avoiding the use of general measures for all areas. This is again in line with the regionalization principle and demands a shift in the modus operandi of the CFP from a traditional centralized top-down, command-control approach toward more regional-specific management which should be, in turn, developed and implemented with stakeholders in a spirit of co-management (Eliasen et al., 2015).

Despite the fishing effort of the BTF has remained relatively low in the Balearic Islands compared to nearby areas, the fishing exploitation has produced noticeable effects on the main demersal resources. As a result of fishing, some target stocks shifted from an early period of under-exploitation to over-exploitation during the late 1970s or early 1980s (Quetglas et al., 2013). This change altered the population resilience of those stocks and brought about an increase in the sensitivity of its dynamics to the climate variability. These results reveal that the marine ecosystems from the Balearic Islands are also sensitive to changing environmental conditions, an issue of paramount importance in the framework of the current climate change. Consequently, the putative effects of global change should also be considered for regional fisheries management which, in turn, will demand an adaptive approach to face those changing conditions. In this sense, the ecosystem-based management is highly-equipped for climate change adaptation (Ogier et al., 2016). As multiple climate-driven changes can induce hard-to-reverse shifts in regional ecosystems, the EAFM becomes a necessity rather than a precautionary approach (Marzloff et al., 2016).

In spite of representing the 85% of EU fleets (European Commission, 2014), SSF are under-represented, or directly neglected, in fisheries assessment and management agendas at national and supranational levels (e.g., Guyader et al., 2013). In the Myfish project, we have included a first in-depth analysis of the SSF from the Balearic Islands using data from official statistics (Quetglas et al., 2016), which are known to be underestimated in the Mediterranean owing to unreported catches (Coll et al., 2014; Pauly et al., 2014). As a consequence, output values of the stock status indicators and the bioeconomic modeling should be taken with care beyond tracking trends in the fishery. Sales of fish outside the official market are especially important in species with high commercial value such as dentex, red scorpionfish, and spiny lobster (Carreras et al., 2015), which are precisely the stocks showing the worst exploitation status. Unreported catches may result in underestimation of fishing mortality, leading to biased stock assessments that hamper achieving a sustainable exploitation (Punt et al., 2006; Bellido et al., 2011). This reinforces the need to sensitize fishermen about the importance of providing the best data possible to scientists in order to help improving the stock assessment and management. The problem of the underreported catches is compounded by the recreational fisheries, which share some of the main SSF target species. In the highly touristic Balearic Islands, where recreational catches represent 43% of the commercial ones (Morales-Nin et al., 2015), this activity might affect seriously the exploitation state of some target stocks. Recreational and competitive spear fishing have a sizeable impact on the depletion of large rocky bottom littoral fish (e.g., *Epinephelus marginatus*) and contributes to the non-profitability of some gears used by the SSF (Coll et al., 2004). Moreover, some of the recreational catches are illegally commercialized, affecting the fish demand of the SSF as well (Merino et al., 2008).

The main aim of fisheries management is the sustainable exploitation of living resources, which also requires the conservation of marine ecosystems (Worm et al., 2009). This is a very important issue in the Balearic Islands where, as already mentioned, the red algae beds (maërl) overlap with traditional fishing grounds of both the BTF and SSF. Consequently, a proper implementation of the EAFM in the area should make compatible the conservation of these habitats and the sustainability of fisheries. This is a great challenge owing to the strong decrease in the number of fishing vessels observed in the Balearic Islands during the last decades. In case such a decrease is maintained, it might lead the fishing sector to its final disappearance, which seems not too far away in the case of bottom trawlers (**Figure 6**). Another option would be to stabilize the fleet in such a low number of trawlers that it will ensure the sustainable exploitation of the resources. In this second case, however, fisheries management should also ensure that such a low number of vessels will also allow the viability and maintenance of the fish market chain, from fishers to consumers. Needless to mention the maintenance of local traditions, culture, and gastronomy within the current framework of a globalized world, especially in an area so highly dependent on tourism as the Balearic Islands. Therefore, urgent measures must be taken to improve both the profitability of commercial fishing and its attractiveness to young people, so as to guaranty the maintenance of sustainable fisheries and the protection of the marine environment.

Although the ecosystem-based management is complex and difficult to operationalize, whereby progresses have been somewhat limited, the steps taken so far are worthy for future progresses (Link and Browman, 2017). The lack of proper datasets is no more an excuse to avoid implementing the EAFM since it is feasible with the information, tools and approaches currently available (Patrick and Link, 2015). This study is a first step toward the implementation of the EAFM in the Balearic Islands by means of the development of a harvest strategy and it is intended to be a working example of co-management (fishers, policy-makers, and scientists) in the Mediterranean in the framework of the new EU CFP.

AUTHOR CONTRIBUTIONS

All authors participated actively in the Myfish project and the development of this Regional Implementation Plan (RIP). Scientists performed all data analyses (AQ, GM, JG, FO, BG, PO, and EM). Stakeholders (AG and AMG) provided information for data analyses and expertise for interpreting results and designing the RIP. All authors contributed to the writing of the manuscript.

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A Holistic Approach to Fishery Management: Evidence and Insights from a Central Mediterranean Case Study (Western Ionian Sea)

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The new Common Fisheries Policy (CFP) is designed to represent an appropriate response to the uncertainties and challenges facing the fisheries sector. It also adopts a holistic approach to fisheries management, considering all factors driving fishers' behavior, and ultimately, the long-term maintenance of living resources. The most reliable way to pursue these aims could be represented by a change in the exploitation pattern, in order to guarantee the sustainability of fisheries without compromising their socioeconomic viability. In this paper, the demersal fisheries of the Ionian Sea [Geographic Sub-area (GSA) 19] were analyzed with respect to their spatial, temporal, economic, and biological characteristics in terms of four key species for fisheries, namely European hake, red mullet, giant red shrimp, and deep-water rose shrimp. Specifically, (1) a quantitative procedure was applied to break down the whole system (including small-scale fleet components) into a series of fishing grounds using input data about fishing efforts; (2) the different fleet segments were defined as a combination of main gear and fishing grounds; (3) the effort and production by fleet segment were derived according to biological samplings of commercial data (Data Collection Framework for the collection and management of fisheries data, DCF), information on localization of nursery and spawning grounds, and expert knowledge; and (4) all this information was used to feed a bioeconomic modeling tool (BEMTOOL), and to explore alternative exploitation patterns. A series of scenarios including the *status quo* were defined, starting from the actual management approach based on temporal fishing closure. The results showed that significant improvements in the exploitation pattern could be achieved by setting up spatial and/or temporal gear-specific bans of the fishing activity. More specifically, scenarios based on a 3-month fishing ban for trawlers are expected to provide high rebuilding of the spawning stock biomass (SSB) for all target stocks, and at the same time, result in a remarkable reduction of discards. When combined with a seasonal fishing ban for small-scale fleets equipped with nets and longlines, this approach could lead to a significant improvement in all indicators, but especially the SSB of the exploited species.

Keywords: spatial management, exploitation pattern, simulations, forecast, sustainability

INTRODUCTION

Following the cornerstone World Summit on Sustainable Development of Johannesburg in 2002, in which the European Union (EU) committed to acting against the continued decline of many fish stocks, the Common Fisheries Policy (CFP; EC, 2013) has been further developed and adapted to guarantee the conservation of marine living resources and the sustainable management of fisheries. The core of the reformed CFP is explicitly identified with the concept of adaptation of fishing activities to exploitation rates that maintain or restore the populations of harvested stocks above levels that can produce the maximum sustainable yield (MSY). Different strategies have been identified in the CFP to pursue this aim, including the effective implementation of an ecosystem approach to fishery management (EAFM) and the progressive reduction of discards. However, the CFP undertakes to ensure the continuation of viable fishing activities while explicitly referring to economic and social components. In fact, the protection of marine living resources and the socioeconomic growth of the fishery sector should not be considered conflicting targets; accordingly, the long-term EU Blue Growth strategy (EC, 2014) intends to promote the growth of the fishery sector.

Recently, following the United Nations Sustainable Development Summit 2015 (New York, 25–27 September), the General Fisheries Commission for the Mediterranean (GFCM) approved the resolution on the midterm strategy (2017–2020) toward the sustainability of Mediterranean and Black Sea fisheries (Resolution GFCM/40/2016/2). This resolution aims to reverse the alarming trend of the status of commercially exploited stocks, while supporting livelihoods for coastal communities and mitigating the effects of fisheries on the ecosystem, by 2020.

In the Mediterranean Sea, the fisheries management is set at the scale of Geographical Sub-areas (GSAs; **Figure 1A**) and based on the control of fishing capacity, selectivity, and effort in space and time; moreover, quota-based approaches have been applied for a few species, including benthic species or highly migratory shared stocks. Given the ineffectiveness of the current Mediterranean management system (Cardinale and Scarcella, 2017), a new generation of approaches is emerging (Holland, 2003; Zeller and Reinert, 2004; McHich et al., 2006; Pelletier et al., 2009; Dunn et al., 2011; Sampson et al., 2011; Bastardie et al., 2014; Campbell et al., 2014; Russo et al., 2014a; Rossetto et al., 2015). These modern approaches have been devised and developed to investigate the status of living resources as a function of the spatial and temporal management of fishing efforts, while some of them also consider socioeconomic consequences and fishery interactions. A common thread of these models is that regulating the access to fishing grounds could be an effective approach for protecting critical life stages and improving the exploitation pattern; this has resulted in a combination of fleet and gear selectivity of different fishing tactics while also considering the accessibility and vulnerability of fish population life stages (Recommendation GFCM/40/2016/4).

This study focuses on the Western Ionian Sea (GSA 19), which is characterized by a narrow continental shelf with a steep slope (Capezzuto et al., 2010; Maiorano et al., 2010). Here, the fishing vessels targeting demersal resources are distributed in the 10 main harbors along the coast (Carbonara, 2013; Carlucci et al., 2015; **Figure 1B**). The authors' direct experiences in DCF (https://ec.europa.eu/fisheries/cfp/fishing_rules/data_collection) fishery samplings have evidenced that the fleets operate in fishing grounds close to the respective harbors and mainly exploit the fishing grounds that are distributed on the shelf and the nearest portion of slope, avoiding moving farther out to reduce both fuel consumption and interference with fleets from other harbors. This spatial fidelity could be proactively used to manage demersal trawling in GSA 19 by regulating the different fleets' access to the diverse fishing grounds. Consequently, deepened characterization of the fishing grounds with respect to both resources and fleets interacting in them could be the first step for the identification of management scenarios aimed at guaranteeing the recovery of stocks and the long-term sustainability of fishing activities. This also in agreement with the regionalized approach (one of the principles of good governance of the CFP), which comprises the implementation of management actions that consider fisheries' regional specificities (EC, 2013).

This study reports on the preliminary results of a new approach that was inspired by the CFP. This involves a combined application of a spatial-based analysis of the fishing effort and a bioeconomic platform that allows simulation and exploration of a large set of management rules.

The original approach is applied to the demersal fishery of GSA 19 (**Figure 1B**). To this aim, the data provided by the Vessel Monitoring System (VMS), Community Fishing Fleet Register (http://ec.europa.eu/fisheries/fleet/index.cfm) data, and DCF biological samplings of commercial data are used to characterize the fishing grounds. Spatially defined fleet segments have been identified that combine the main gear and the fishing ground. Then, the derived information on the effort, exploitation pattern, and production by fleet segment are used as input for an integrated bioeconomic modeling tool (BEMTOOL; Rossetto et al., 2015; Spedicato, 2016). The BEMTOOL platform was developed in the Mediterranean Halieutic Resources Evaluation and Advice (MAREA) framework project (MARE/2009/05-Lot 1) to inform and support the management of stocks and fleets. BEMTOOL was applied to forecast the biological and socioeconomic effects of different management scenarios, including temporal gear-specific bans and alternate closures of selected fishing grounds. The BEMTOOL platform allows forecasting how different harvesting and management strategies affect the dynamics of the following: (1) the spawning stock biomass (SSB) under different conditions of exploitation; and (2) fishing mortality and the related fishery outputs in terms of total and by-fleet-segment catches (separating landings and discards) and revenues.

As observed by Froese et al. (2016), no attempt has been made so far to disentangle two different effects influencing the size structure of an exploited population, namely fishing mortality and the minimum size limits. The scenarios were specifically designed to make a first attempt at disentangling these two effects based on the time of offspring of the investigated species.

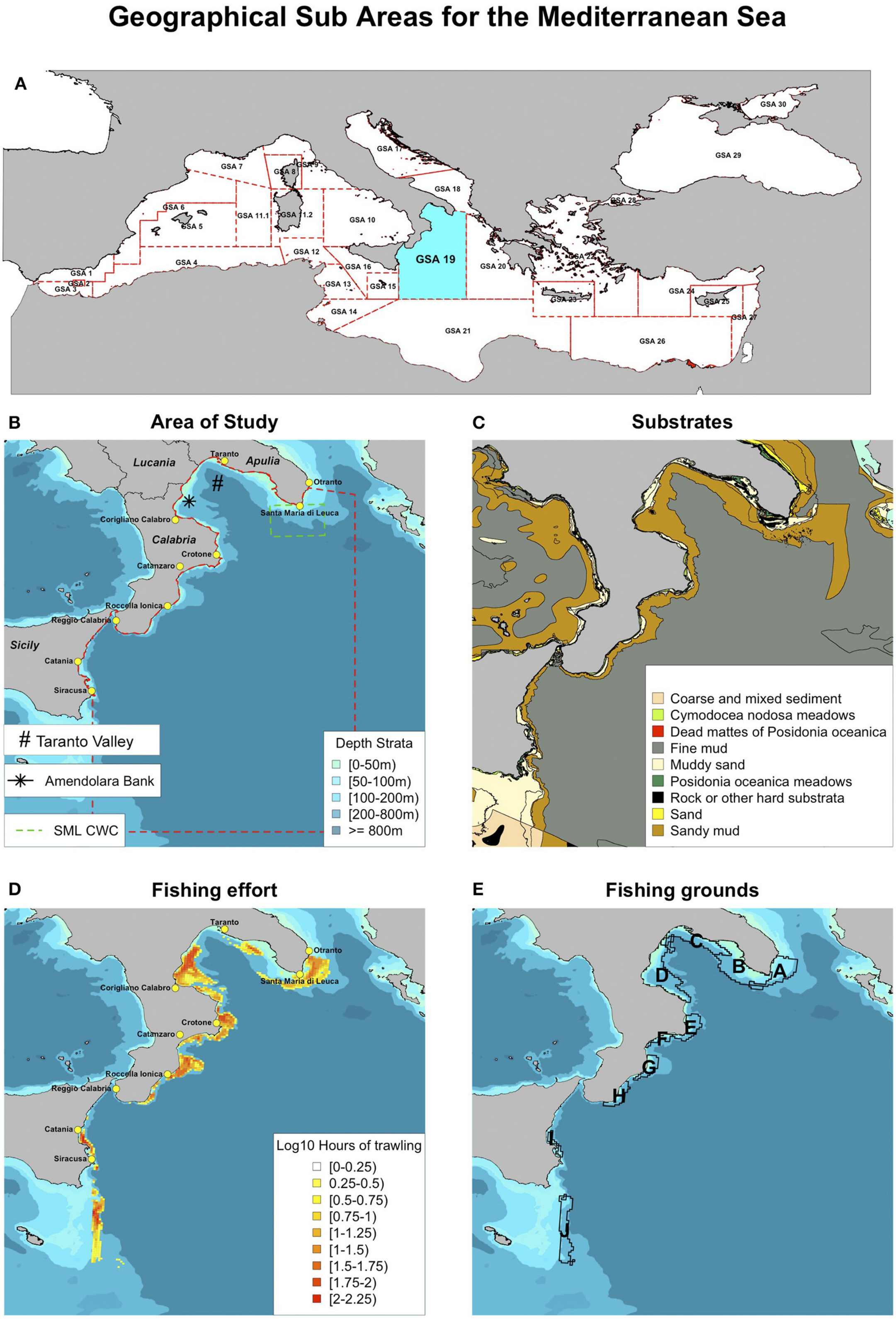

FIGURE 1 | (A) The fisheries management set at the scale of Geographical Sub-Areas in the Mediterranean Sea; **(B)** Study area (GSA 19) with the main bathymetric strata and the harbors; SML CWC stands for Santa Maria di Leuca cold-water coral; **(C)** sea bottom substrates as derived from the European Marine Observation Data Network (EMODnet) Seabed Habitats project (www.emodnet-seabedhabitats.eu/); **(D)** yearly trawling effort (mean for 2008–2015) for vessel monitoring system (VMS)-equipped vessels with a length-over-all (LOA) >15 m with respect to a 3 × 3 km grid; **(E)** fishing grounds returned by the constrained clustering analysis.

Scenarios' results were evaluated in terms of the benefit for the SSB of target stocks, decrease of the overall fishing mortality, lowering of the landing, and reduction of the discards.

MATERIALS AND METHODS

Study Area

The GSA 19 covers a surface of about 16,500 km^2 (MEDITS, 2016) in the depth range of 10–800 m along a coastline of about 1,000 km encompassing four administrative regions, namely Apulia, Lucania, Calabria, and Sicily (Maiorano et al., 2010; **Figure 1B**). The Western Ionian Sea is geomorphologically divided into two sectors by the Taranto Valley, which exceeds 2,200 m in depth. The former is located between the Taranto Valley and the Apulia region and is represented by a broad continental shelf. Along Calabria and Sicily, the shelf is generally extremely limited, with the shelf break located at a depth of 30–100 m. Many submarine canyons are located along these coasts, playing an important role in the transport of terrigenous debris from coastal waters to deeper grounds. These habitats are unsuitable for trawling and represent a sheltered site for species during sensitive phases of their lifecycles (Capezzuto et al., 2010).

In the circalittoral zone along the Apulia and Calabria coasts, a fine mud substrate is evident, with the biocenosis of the terrigenous mud widespread from a depth of 70–80 m (**Figure 1C**). Specifically, the biocenosis of the detritic shelf-edge, always within the fine mud substrate, is often characterized by the dominance of the sea lily *Leptometra phalangium*, which is distributed on the shelf edge throughout the Western Ionian Sea; over the continental slope, the biocenosis of the bathyal mud extends, with the facies characterized by *Funiculina quadrangularis* and *Isidella elongata*, even if it has almost completely disappeared due to trawling. These two facies are often associated to the presence of commercial species, such as the deep-water pink shrimp (*Parapenaeus longirostris*) and Norway lobster (*Nephrops norvegicus*) for the former and blue and red shrimp (*Aristeus antennatus*) and giant red shrimp (*Aristaeomorpha foliacea*) for the latter.

Two important habitats have been recognized far from the Apulian and Calabrian coasts, namely the Santa Maria di Leuca cold-water coral (SML CWC) area and the Amendolara Seamount, respectively (**Figure 1B**). The SML CWC represents a rare example of living *Madrepora*-dominated coral communities distributed over an area of about 2,000 km^2 between about 120 and 1,400 m in depth (D'Onghia et al., 2010, 2012, 2016; Vassallo et al., 2017). Fishing activities using mostly trawl nets and longlines are carried out around the SML CWC (D'Onghia et al., 2012, 2016). In fact, the presence of coral mounds is known to the local fishermen, who experience gear damage and losses. Considering the effect of trawling, and to a lesser extent, other fishing gear, the GFCM created a new legal category of Fishery Restricted Area (FRA) on the SML CWC, recommending the prohibition of towed gears. However, to date, no effective management measures have been adopted, and unauthorized operation may still take place close to or even inside the northward limit of the FRA (D'Onghia et al., 2016). The Amendolara seamount southwestern Capo Spulico extends over an area of about 31 km^2, rising from 200 up to about 20 m below the surface. The Amendolara seamount is characterized by coarse sand and coastal detritic biocenoses, as well as a wide diversity of fish, crustaceans, and cephalopods sought by local fishers.

The main target species in landing value and volume of the more relevant fisheries in GSA 19 are as follows: European hake (*Merluccius merluccius*), red mullets (*Mullus barbatus* and *Mullus surmuletus*), cuttlefish (*Sepia officinalis*), octopus (*Octopus vulgaris*), common Pandora (*Pagellus erythrinus*), deep-water rose shrimp, giant red shrimp, and blue and red shrimp. These stocks are mainly exploited by vessels, with a length-over-all (LOA) of 6–12 m, for the small-scale fishery, and with a LOA of 12–18 m for the trawlers.

Six main demersal fisheries have been identified in the GSA [Scientific Technical and Economic Committee for Fisheries (STECF), 2015], as follows: set longlines targeting demersal fish, set gillnets targeting demersal species, trammel nets targeting demersal species, bottom otter trawl targeting demersal species, bottom otter trawl targeting deep-water species, and bottom otter trawl targeting mixed demersal and deep-water species. **Figure 2** shows the relationship between species distributions in the different fishing grounds and effort activity/target species for the different fleet segments.

Data

Different types of data were used for the objectives of this study, as follows:

1. VMS data, which were employed for inferring the activity and fishing effort of vessels with a LOA >15 m at a fine spatial level;
2. The number of vessels, gross tonnage (GT), power (KW), and LOA from the Community Fishing Fleet Register in 2008–2015 for all the types of vessels;
3. Fishing activity (average fishing days per vessel) from DCF effort data and VMS data;
4. Landings and discards of the main target species by gear and fleet from DCF production data;
5. Fleet selectivity by gear and fishing ground, derived from the composition of catches observed in DCF biological samplings of commercial data; and
6. Localization of nursery and spawning grounds of the target species from Mediterranean Sensitive Habitats—MEDISEH project outcomes (European project MEDISEH from MAREA Framework).

A detailed description of these data is given below.

The activity of fishing vessels with a LOA larger than 15 m was analyzed using the data provided by the VMS. The VMS was introduced by the European Union for remote control of fishing vessels (EC, 2003, 2009), and it consists of an automatic transmitting station (the so-called blue box), which periodically sends information about vessel position, speed, and prow heading (EC, 2011) via satellite transmission. VMS data are widely used in the scientific literature for the analysis of fishing effort patterns (Lee et al., 2010; Campbell et al., 2014; Joo et al., 2015) and the assessment of fishing impacts (Gerritsen et al., 2013; Eigaard et al., 2016; Russo et al., 2016b). The VMSbase R package (Russo et al., 2014a), which implements the procedures described in

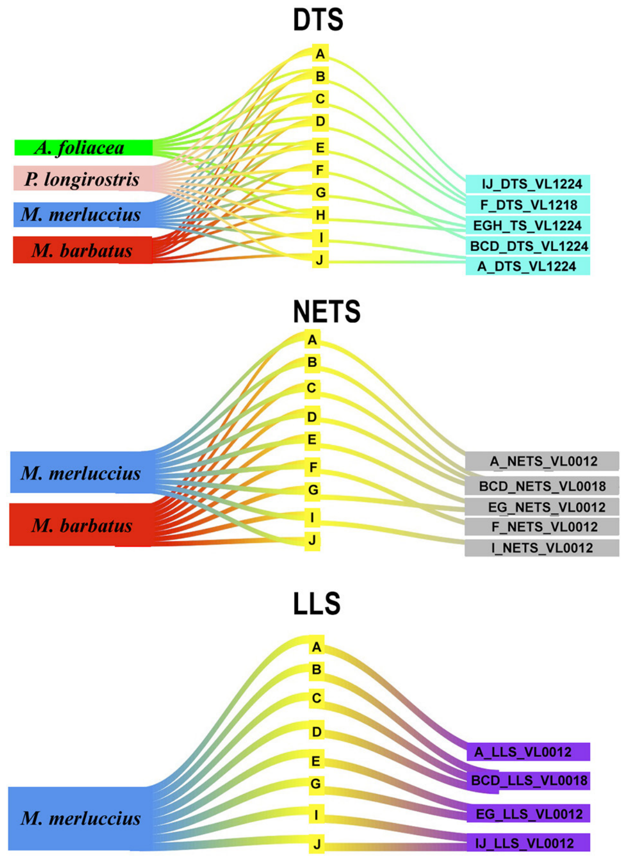

FIGURE 2 | Sankey plots (Weiner, 2015) representing the relationship between species distributions in the different fishing grounds and effort activity/target species for the different fleet segments. DTS stands for bottom otter trawl, NETS stands for gill net and trammel nets, LLS stands for longliners, the fishing grounds of activities are coded from A to J. VL stands for vessel length. The fleet segment codification is built as a concatenation of fishing ground, gear, and vessel length range.

Russo et al. (2011a,b); Russo et al. (2013, 2016a), was used to process the VMS data related for the full examined temporal range, comprising the years 2008–2015 (8 years). A complete description of the standard procedure to obtain high-frequency (10 min) fishing set positions and then a quantitative assessment of trawling effort is reported in Russo et al. (2014a). Basically, this procedure comprises the following steps: (1) data cleaning (removal of redundant or erroneous pings); (2) partitioning of VMS data with respect to the fishing trips (sequence of pings starting from and ending at a given harbor) of each fishing vessel; (3) interpolation to increase the native frequency (ranging between 1 and 2 h) to 10 min; (4) estimation of the sea bottom depth corresponding to each interpolated ping using the function provided by the "marmap" package (Pante and Simon-Bouhet, 2013); and (5) identification of fishing set positions using a combined speed/depth filter.

At the end of this procedure, a dataset containing the fishing set positions (defined by two spatial and one temporal coordinates) for 94 vessels operating in the GSA 19 was obtained. These 94 trawlers were selected from a larger list of over 200 vessels based on a screening of their activity with respect to the set of 32 seasons (from winter 2008 to autumn 2015). Thus, trawlers monitored in fewer than eight quarters in the time series of 2008–2015 were excluded from the actual fleet exploiting the study area.

According to the Community Fishing Fleet Register, in 2008–2015, small-scale fleet segments counted 1,141 vessels registered in 26 ports. These vessels were classified as using nets [gillnets (GNS) and trammel nets (GTR)] and longlines (LLS) as prevalent gears. Annual data on vessels' characteristics (GT, KW, number of vessels by port) were available aggregated by gear and LOA.

In this analysis, we retained 857 vessels (75.1% of the small-scale fleet) from the 18 ports linked to the 10 fishing grounds identified with VMS data. The DCF landing and discard data by species were extracted by the Mediterranean and Black Sea DCF official website (https://stecf.jrc.ec.europa.eu/dd/medbs).

The landing of the three fleet components considered in the case study (trawlers, nets—gillnets and trammel nets—and longlines) represents 62% of the total production of the area (DCF data for 2015). The target species considered are European hake, red mullet, deep-water pink shrimp, and giant red shrimp, representing 33% of the total landing of the selected fleet components.

The length frequency distributions of these species observed in the DCF biological samplings of commercial data (catch by gear) were used to drive the modeling of the exploitation pattern (selectivity) for each fleet segment. This information was also corroborated by data related to the location of sensitive habitats (nursery areas and spawning grounds) derived from the MEDISEH project (Figure S1 in Supplementary Material).

Identification of Fishing Grounds

The VMS dataset was divided into a set of 32 seasons (from winter 2008 to autumn 2015), and for each season, the total amount of fishing days was registered for each cell of a 3 × 3-km^2 grid defined for the whole GSA 19. This allowed a graphical inspection of 32 maps of the fishing effort (not reported for the sake of brevity). This inspection revealed that the trawling effort is basically distributed in a short number of spatially separated unit groups of cells. This pattern persists when the mean yearly pattern is inspected (**Figure 1D**).

The best partitioning of grid cells with respect to the mean yearly pattern of the trawling effort was identified using the constrained clustering approach provided by the "skater" function of the R package labeled "spdep" (Bivand et al., 2016). This analysis returned a set of 10 fishing grounds (**Figure 1E**), representing the list of areas—defined as sets of contiguous cells—representing the "playing field" for the fishing activity. It should be observed that the constrained clustering applied on the mean yearly trawling effort confirmed the visual pattern represented in **Figure 1D**. Each of these fishing grounds was evaluated using the information on the localization of nurseries and spawning grounds of the main target species in the present study.

The total number of vessels using nets and longlines was obtained from 2008 to 2015 by splitting the overall number of vessels with main gear nets and longlines in the For every quarter, each vessel was assigned to a unique fishing ground according to the percentage of fishing days; this avoided counting a vessel more than once. The seasonal activity of trawlers with respect to the 10 fishing grounds obtained from the VMS data was integrated by combining expert knowledge (regarding target species and fishing behavior) and the data collected on board commercial vessels during the sampling activities of the Data Collection Framework (EC, 2008) in the GSA 19 (e.g., Carbonara, 2013, 2015). Based on the LOA and target species of the visiting vessels, the 10 main fishing grounds were then aggregated in five trawling areas corresponding to five fleet segments (**Table 1**).

The number of average fishing days, GT, and KW per fishing ground for trawlers was seasonally derived from VMS data based on the vessels visiting the fishing grounds. To include trawlers that are not obliged to use the VMS (LOA of 12–15 m), a multiplicative correction factor was applied to the vessels, average GT, and average KW of each identified fleet segment (combination of gear and fishing ground) using the VMS. The correction factor was given by the ratio between the number of vessels (between 12 and 24 m and with trawl as main gear) reported in the Community Fishing Fleet Register and the number of vessels monitored by the VMS that were allocated to the same fishing grounds. The final number of fishing vessels by fleet segment is reported in Table S1 in the Supplementary Material, while the correction factors applied are reported in Table S2 in the Supplementary Material.

Regarding the small-scale fleet segments, the association between the vessels registered in each port and the fishing grounds was determined by cross-checking the expert knowledge on fishing habits and data from on-board biological sampling from DCF observations. Finally, nets and longlines were divided into five and four fleet segments, respectively (**Table 1**). The estimation of the number of vessels by gear and fishing grounds were obtained according to the following steps:

(i) The total number of vessels using nets and longlines was obtained from 2008 to 2015 by splitting the overall number of vessels with main gear nets and longlines in the Community Fishing Fleet Register according to the DCF production data; and

(ii) The number of vessels per gear obtained in the previous step was split among the fishing grounds proportionally to the units registered in each port (and thus associated with each fishing ground) according to the Community Fishing Fleet Register, under the assumption that small-scale vessels operate closer to the associated port than larger vessels do.

The related fishing effort deployed was obtained in terms of average number of fishing days by gear and year, and it was estimated by dividing the total number of fishing days carried out in the GSA, as obtained from the DCF data, by the number of vessels derived in step (i). The seasonality of fishing was determined according to the quarterly DCF activity data, assuming that all the fleet segments engaged in the same fishing activity used nets or longlines. The average GT and KW per vessel were derived by the Community Fishing Fleet Register, averaging the values of the vessels registered in the selected ports by main gear (Table S3 in Supplementary Material).

Association of Landings/Discards with Fishing Grounds and Fleet Segments

The times series of landings and discards for the four target species were obtained from the official DCF data. However, these data were not associated with the spatially defined fleet segments identified in the present work. To obtain this aggregation level, the production by gear and species was split among the spatially defined fleet segments by combining the information on fishing effort (number of vessels and KW) and the probability of finding a nursery and/or a spawning ground hotspot (as from the MEDISEH project outputs) in the associated fishing ground,

TABLE 1 | Fleet segment definition with respect to the gear (DTS stands for bottom otter trawl, NETS stands for gill net and trammel nets, LLS stands for longliners), the fishing grounds of activities, and the target species: *M. merluccius*, *M. barbatus*, *P. longirostris*, *A. antennatus*.

Fleet segment codification	Gear	Length class (VL range in m)	Cluster (by fishing grounds)	Target species
A_DTS_VL1224	DTS	[12–24)	A	DPS, MUT, HKE
BCD_DTS_VL1224	DTS	[12–24)	B,C,D	DPS, HKE, MUT, ARS
EGH_DTS_VL1224	DTS	[12–24)	E,G,H	DPS, HKE, ARS,MUT
F_DTS_VL1218	DTS	[12–18)	F	MUT, DPS, HKE
IJ_DTS_VL1224	DTS	[12–24)	I, J	DPS, MUT, HKE
A_NETS_VL0012	NETS	[00–12)	A	MUT, HKE
BCD_NETS_VL0018	NETS	[00–18)	B,C,D	MUT, HKE
EG_NETS_VL0012	NETS	[00–12)	E,G	MUT, HKE
F_NETS_VL0012	NETS	[00–12)	F	MUT, HKE
I_NETS_VL0012	NETS	[00–12)	I, J	MUT, HKE
A_LLS_VL0012	LLS	[00–12)	A	HKE
BCD_LLS_VL0018	LLS	[00–18)	B,C,D	HKE
EG_LLS_VL0012	LLS	[00–12)	E,G	HKE
IJ_LLS_VL0012	LLS	[00–12)	I,J	HKE

VL stands for vessel length. The fleet segment codification is built as a concatenation of fishing ground, gear and vessel length range.

according to the following relationship:

$$L_{y,fs,g,s} = L_{y,g,s} * \frac{NbVess_{y,fs,g} * KW_{y,fs,g} * sens\_score_s}{\sum_{fs} NbVess_{y,fs,g} * KW_{y,fs,g} * sens\_score_s}, \qquad (1)$$

where L is the landing, y is the year, f is the fleet segment, g is the gear (trawlers, nets, and longlines), and $sens\_score_s$ is a weight calculated as 1 + the mean probability of finding a hotspot (nursery or spawning ground) in the fishing ground of species s. A similar procedure was followed to split the discards.

Through this relationship, landings and discards are assumed positively and linearly dependent on the number and power of vessels, as well as the availability of stock in the fishing ground. The total landing was split using the same formula, omitting the *sens_scores* coefficients. The consequences of three management scenarios alternative to the *status quo* were investigated using the BEMTOOL model (Rossetto et al., 2015; Spedicato, 2016; see Section Simulated Scenarios in BEMTOOL).

Modeling: The BEMTOOL Platform

The BEMTOOL platform incorporates six operational modules, as follows: Biological, Pressure (the core model is ALADYM; Lembo et al., 2009), Economic, Behavioral, Policy/Harvest Rules, and Multi Criteria Decision Analysis (MCDA). BEMTOOL follows a multi-fleet approach and simulates the effects of several management trajectories on stocks and fisheries on a fine time scale (month). The model accounts for fleet interactions, length/age-specific selection effects, discards, and socioeconomic performance. A wide set of biological, pressure, and economic indicators is the default output. In this study, SSB, landings, discards, and revenues were considered the prominent indicators.

The most recent results presented in the STECF and GFCM stock assessment working groups for the Mediterranean were used to parameterize the different components of BEMTOOL model. Specifically, the results of the following assessments were used: European hake (FAOSAC, 2015), red mullet (FAOSAC, 2014), giant red shrimp [FAOSAC, 2014; Scientific Technical and Economic Committee for Fisheries (STECF), 2016b], and deep-water rose shrimp (Facchini et al., 2016; FAOSAC, 2017).

In **Table 2**, a summary of the biological parameters is presented, while the recruitment and total mortality times series used to simulate each stock in hind-casting mode are shown in Figure S3 in the Supplementary Material. The same natural mortality was assumed in all years (Figure S3 in Supplementary Material).

The uncertainty (process error) implemented in the model following the Monte Carlo paradigm allows a risk evaluation in terms of sustainability of the different management strategies. The process error was implemented using a lognormal multiplicative error with a mean of 0 and standard deviation of 0.3. This error was applied to the recruitment to take into account the uncertainty due to the process error; in turn, this was propagated to all relevant output indicators. Given that stock recruitment relationships were not available for the stocks studied in the present paper, a geometric mean of the last 3 years (recruitment values from the most recent stock assessments) was used for projecting the populations.

The effort of the different fleet segments was simulated according to the capacity, activity, power, and GT described in Section Identification of Fishing Grounds. Figure S4 in the Supplementary Material reports the selectivity functions used to shape the fishing mortality of the different stocks and fleet segments by size and age.

Discards were considered only for deep-water rose shrimp, European hake, and red mullet; they were negligible and not considered in the assessment of giant red shrimp. The discard volume was modeled according to a reverse ogive, with the following lengths at which 50% of individuals are discarded: 17 cm of total length for European hake, 10.5 cm of total length for red mullet, and 17 mm of carapace length for deep-water rose shrimp.

The revenues by species were by estimated applying average prices of each target species to the landing per species [Scientific Technical and Economic Committee for Fisheries (STECF), 2016a]. The same price was applied to all fleet segments. The total annual revenues of past and current years were approximated by means of a correction factor estimated by gear for 2013 (Mannini and Sabatella, 2015), which was given by the following formula:

$$cf_{rev,g} = \frac{TL_g * p_g}{\sum_s L_{s,g} * p_s}, \qquad (2)$$

where TL is the total landing by gear g, p_g is the average price for the whole production for gear g, L_g is the landing of species s for gear g, and p_s is the price of species s. The same correction factor was used to derive the total revenues in the forecast. The total landings by fleet segment in the forecast years were estimated with a correction factor calculated as the ratio between total landings and the sum of the target species in 2015.

Prices of all the target species were assumed to be inversely dependent on total landings according to the following relationship, with the elasticity coefficient equal to −0.2 (Camanzi et al., 2010):

$$p_{s,fs,t} = p_{s,fs,t-1}\left(1 + \varepsilon_{s,fs,landing}\frac{L_{s,fs,t} - L_{s,fs,t-1}}{L_{s,fs,t-1}}\right), \qquad (3)$$

where $p_{s,fs,t}$ is the price of the target species s for fleet segment fs at time t, $L_{s,fs,t}$ is the landings of the target species s for fleet segment fs at time t, and $\varepsilon_{s,fs,landing}$ represents the elasticity coefficient price-landings for species s and fleet segment fs (in €/kg).

Simulated Scenarios in BEMTOOL

A series of scenarios, including the *status quo*, was tested, and the effects of these scenarios were forecasted for the year 2023. This allowed to consider the time span in which the cohorts of the population of the longer-living species (European hake, about 15 years) in the pool of the target stocks reached the bulk for biomass. The definition of the scenarios was based on the reasoning that a temporal stop of fishing activity, for a whole calendar month, is already applied, and thus, there may be a higher level of acceptability for managers and stakeholders.

TABLE 2 | Biological parameters per stock $\boldsymbol{L_\infty}$, $\boldsymbol{K}$, and $\boldsymbol{t_0}$ von Bertalanffy growth parameters, and *b* length-weight relationship coefficients, size at first maturity (L_{50}), and maturity range (MR).

Species	Sex	L_∞	K	t_0	a	b	L_{50}	MR	Units
HKE	F	104	0.2	−0.01	0.0047	3.12	33.6	2.4	cm-g
	M	104	0.2	−0.01	0.0047	3.12	17.5	1.1	cm-g
MUT	F	30	0.4	−0.3	0.0072	3.17	11.2	3	cm-g
	M	30	0.4	−0.3	0.0072	3.17	11.2	3	cm-g
DPS	F	46	0.575	−0.2	0.0043	2.376	16	5	mm-g
	M	40	0.68	−0.25	0.0043	2.376	16	5	mm-g
ARS	F	73	0.438	−0.1	0.00126	2.65	36	3	mm-g
	M	46	0.5	−0.1	0.00106	2.73	28	3	mm-g

A temporal stop is also generally viewed as a non-irreversible measure that can leave more room in the sector to adapt to possible social and economic consequences of management actions. To evaluate the performance of additional seasonal fishing bans to the 1-month measure already in place for trawlers in the area, three strategies were designed and projected for 2023 in addition the *status quo*, as follows:

- (S1) *Status quo*: fishing activity projected as in the current situation;
- (S2) Seasonal fishing ban for all trawlers in June and July (Seasonal FB DTS);
- (S3) Differentiated fishing ban for trawlers, as reported in **Table 3** (Rotated FB DTS); and
- (S4) The same as Scenario 3 with the addition of the following:
- An extended seasonal fishing ban for A_DTS_VL1224, BCD_DTS_VL1224, and IJ_DTS_VL1224 in August (for half a month); and
- A seasonal fishing ban for small-scale fleets—longlines stopped from January to March and nets in May and November (Fishing ban extended ALL).

The rationale of scenario 2 was to extend the seasonal fishing ban for all trawlers for the 2 months with a remarkable occurrence of recruits of the target species considered in the present paper.

The aim of scenario 3 was to search for a trade-off between the need to reducing the fishing impact while ensuring a certain availability of landings, which is generally considered an issue by fishers. The differentiated fishing ban was conceived to seasonally stop the following:

- Fleets with a higher share of production (BCD_DTS_VL1224 and A_DTS_VL1224 fleet segment) in June and July, as in scenario 2;
- Fleets EGH_DTS_VL1224 and F_DTS_VL1218, which have deep-water rose shrimp and giant red shrimp as their main targets in April and March, months that are quite important for the recruitment of these species; and
- Fleet IJ_DTS_VL1224 in April and October, given the presence of European hake and deep-water rose shrimp, for which recruitment is important in these months, in the macro-area of the hotspot nurseries.

TABLE 3 | Differentiated fishing ban related to scenario S3.

Fleet segment codification	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A_DTS_VL1224						▨	▨					
BCD_DTS_VL1224						▨	▨					
EGH_DTS_VL1224				▨	▨							
F_DTS_VL1218				▨	▨							
IJ_DTS_VL1224				▨						▨		

The gray cells stands for month of fishing ban.

Scenario 4 aimed to further reduce the fishing mortality for all the fleets, thereby limiting the impact of the fleet segment generally targeting the adult component of the target stocks. The change in activity (number of days × vessels) is shown in Table S4 of the Supplementary Material for each fleet segment and scenario.

RESULTS

Regarding the identification of fishing grounds (**Figure 1E**), it is remarkable that the fishing ground A overlaps with the persistent nursery areas of European hake and giant red shrimp, located on the shelf and shelf break/upper slope between Otranto and Santa Maria di Leuca, respectively (Figure S1 in Supplementary Material). On the same fishing ground, there is also an overlap in the spawning areas of giant red shrimp and deep-water rose shrimp (Carlucci et al., 2009; Colloca et al., 2015; Druon et al., 2015; Figure S1 in Supplementary Material). Fishing grounds B and C, in the areas off Gallipoli and Taranto, respectively, share common characteristics. Specifically, the nursery area of giant red shrimp and the spawning area of deep-water rose shrimp are exploited in both fishing grounds (**Figure 2**).

The spawning area of red mullet observed offshore at Policoro on the shelf bottoms down to 100–150 m seems to be shared between fishing grounds C and D (**Figure 2**). However, this fishing ground also seems to be characterized by the exploitation of European hake, giant red shrimp, and deep-water rose shrimp around the Amendolara Seamount, on the shelf and shelf break/upper slope, respectively.

The fishing grounds off Crotone (E) and Roccella Ionica (G) seem to be exploited for catching blue and red shrimp and giant red shrimp. Indeed, the configuration of the bottom, with its extremely narrow shelf, is suitable for deep fishing. These fishing grounds also include the nursery areas of deep-water rose shrimp on the shelf break and the spawning area of deep-water rose shrimp on the upper slope. Furthermore, the fishing grounds of Catanzaro (F) and Reggio Calabria (H) are located on the shelf, where a spawning area of red mullet was detected overlapping with the biocenoses of coarse and fine well-sorted sands and the biocenoses of terrigenous muds.

Fishing ground I (area off Catania) includes an aggregation area for the recruits and spawners of deep-water rose shrimp (Figure S1 in Supplementary Material). In this fishing ground, a partial overlap with the shallower nursery area of European hake and the spawning area of red mullet also occurs on the bottom down to a depth of 200 m (**Figure 2**).

Finally, fishing ground J, south of Portopalo di Capo Passero, is an area where the trawling activity is concentrated from late spring to the autumn. The main target species is deep-water rose shrimp. Indeed, this fishing ground includes aggregation areas for both recruits and spawners.

The major amount of production is caught by the fleet segments fishing in fishing grounds B, C, and D for all species under consideration. Especially, about the 85% of the deep-water rose shrimp production is fished by fleet segments BCD_DTS_VL1224 and IJ_DTS_VL1224. The results of the associations among landings/discard and fishing grounds-fleet segments are reported in the Supplementary Material (Figure S2).

Considering the simulation of management scenarios, the model results highlight the highest rebuilding of the SSB for all target stocks in S4, whereas maintaining the *status quo* in terms of fishing activity and exploitation pattern would lead to the lowest predicted SSB level (**Figure 3**). This is expected because, among the tested management strategies, S4 was devised to have a more efficient impact on the reduction of fishing mortality

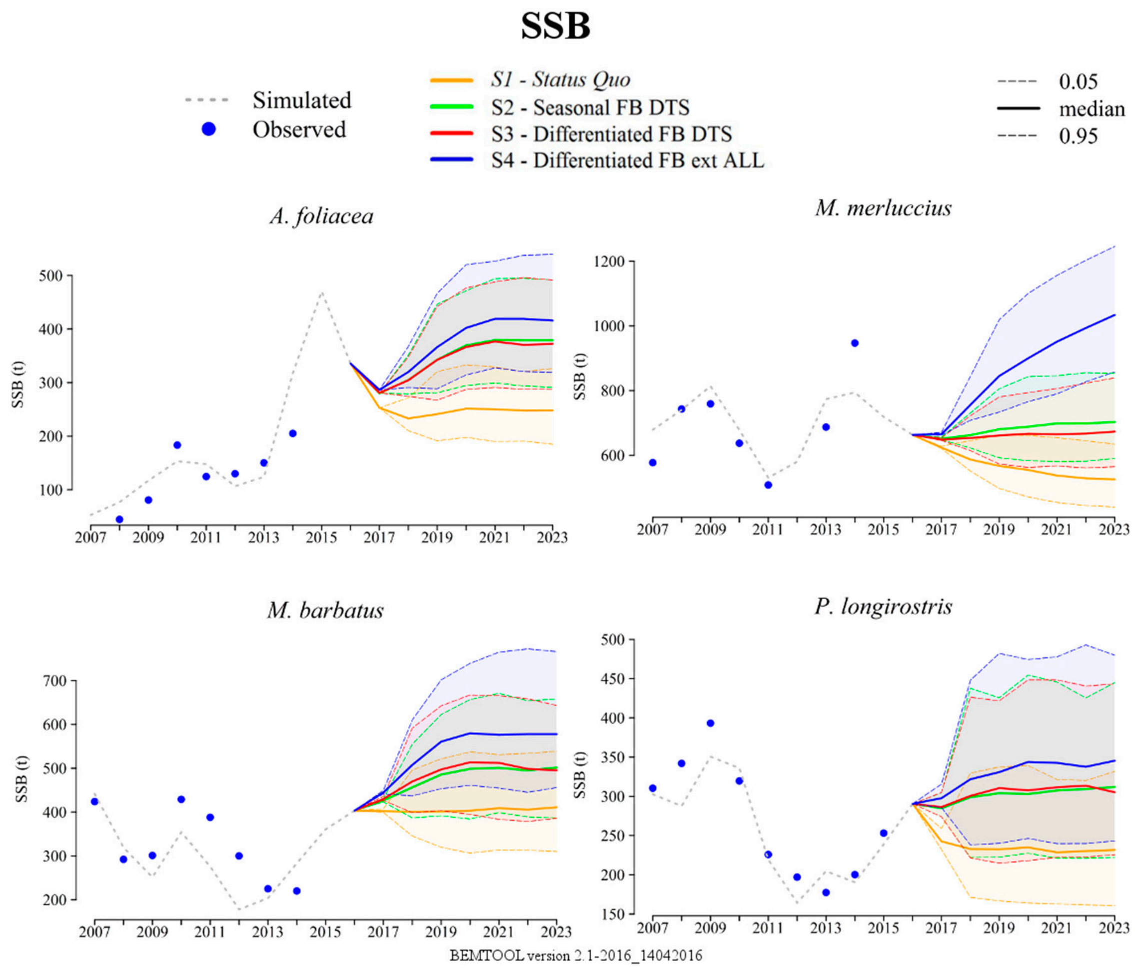

FIGURE 3 | Comparison among the scenarios for the spawning stock biomass (SSB) of the four target stocks in the hindcasting (2007–2016) and forecasting (2017–2023) timelines. Dotted line, Hindcasting from the bioeconomic modeling tool (BEMTOOL); Blue points, estimates from stock assessments.

and the change in the exploitation pattern through a seasonal fishing ban affecting all fleet segments in several periods. These periods span almost all year round, with an overlap of only 2 months among the fleet segments EFGH_DTS, IJ_DTS, and nets.

The projections of discards (**Figure 4**) show that S3 and S4 have similar results, as discards are exclusively due to trawlers and the two scenarios differ only by a seasonal fishing ban that is half a month longer for trawlers in S4. Moreover, the seasonal fishing bans involving nets and longlines do not affect discards. The lowest values of discards correspond to S2 for deep-water rose shrimp and European hake, while lesser discards of red mullet are predicted in S3 and S4.

For European hake and giant red shrimp, the forecasts of landings (**Figure 5**) under S2 and S3 do not differ substantially from the *status quo*, exhibiting only a slight improvement. This effect is amplified for European hake under S4 (**Figure 5**), given that the landing of this stock is made up of 40% from trawlers and of 60% from nets and longlines (**Figures 6**, **7**).

If the fleet segments are considered, the landings of trawlers predicted for 2023 for the *status quo* slightly exceed (upper limit of confidence intervals) those of S2, S3, and S4, except for giant red shrimp, which presents the same slight improvement in the alternative scenarios. This was expected, as the fleet segment BCD_DTS_VL1224—which is responsible for most fishing activity in the area—has the higher share (86%) of production for this species. Indeed, the landing projections produced extremely similar results, as this fleet segment halts in June and July in all the three scenarios.

Interestingly, the model outcome revealed that the rotated fishing ban of DTS (S3) would result in less severe reductions in the landings for all gears and revenues for all the species than the seasonal DTS fishing ban (S2) would, while showing an equivalent improvement in SSB (**Figure 8**). Especially, for European hake, S4 shows basically the same performance as the *status quo* for DTS landing, but it leads to slightly better results for longlines and nets. Nevertheless, setting the fishing ban even for net fleet segments would frustrate the advantages in terms of red mullet landings from other fleets that could be obtained if the fishing ban were applied only to trawlers, both in the seasonal and differentiated strategies. For longliners and nets targeting European hake, the level of predicted landings for 2023 is comparable in the three scenarios and slightly higher than in the *status quo* (**Figure 7**).

The performances of the three scenarios compared to the *status quo* are synthesized in **Figure 9**, considering the percentage variations of the contributions of the six main model-based indicators, as follows: SSB, landings of target species, landings of other species, discards, revenues for target species, and revenues for other species. S4 is expected to give better results in terms of the different indicators, but focusing on SSB, this would increase considerably compared to the other two scenarios. However, the global performances of S2 and S3 were extremely similar, and the effects of the two scenarios are equivalent in terms of overall influence on the pool of indicators considered in the predictions.

DISCUSSION

As a first general consideration, the results of this study support the idea that managing the access to fishing grounds by means of gear-specific regulation could have relevant effects on both the status of living marine resources and the economic aspects of fisheries. This is in agreement with previous theoretical explorations (Holland, 2003; Zeller and Reinert, 2004; Pelletier et al., 2009; Dunn et al., 2011; Dowling et al., 2012; Rassweiler et al., 2012; Russo et al., 2014b; Scarcella et al., 2014; Spedicato, 2016) and empirical observations (Begg and Marteinsdottir, 2003; Rouyer et al., 2008) in this field. However, the novelty of this study could be evidenced mainly in the following elements:

(i) While previous studies combined different data sources, such as VMS and landing data (Campbell et al., 2014) or VMS and logbooks (Chang, 2011; Gerritsen and Lordan, 2011; Russo et al., 2016b) to investigate the behavior and potential management of large vessels, the present study instead considered all relevant fleet segments (including small-scale fisheries) with their specific spatial allocation and gear, modeling, and forecasting of management effects;

(ii) We integrated a wide heterogeneous set of data and expert knowledge to characterize fleet segments through their effort, production, and selectivity. These sets of information ranged from satellite tracking device (i.e., VMS) data to empirical observations carried out within the routine DCF activities. This characterization of fisheries dynamics has been crucial for the simulation approach;

(iii) A considerable effort was devoted to the design of specific scenarios calibrated to the characteristics of the fisheries and the main target resources of the study area; and

(iv) All aspects of fishing activity, from revenues to discards, were considered, thereby anticipating the next challenge of fisheries management regarding the landing obligation [Scientific Technical and Economic Committee for Fisheries (STECF), 2015].

In the Mediterranean, stock conditions and fleet production are generally impaired by a combination of high fishing mortality and suboptimal exploitation patterns, with many small-sized catches determined by technical characteristics, such as the small mesh size in the trawl cod-end. In fact, some recent studies have reported that a rough reduction in the fishing mortality without any change in the fishing selectivity will not determine rebuilding of stock biomass and maintenance of fisheries' yields and revenues at an acceptable level (Colloca et al., 2013). The results of the present paper confirmed this finding, showing that the potential losses caused by the reduced activity were overcompensated by the positive effect of such reduction on the stock productivity. Moreover, stock rebuilding (occurring when the exploitation pattern changes toward larger sizes in species with longer life spans) and the effect of reduced pressure are thus propagated over several cohorts. Looking back at the seminal works in fisheries sciences (e.g., Beverton and Holt, 1957), the optimal fishing mortality for an exploited stock relies on the relative exploitation pattern. This means that a simple reduction in the fishing mortality cannot guarantee sustainable

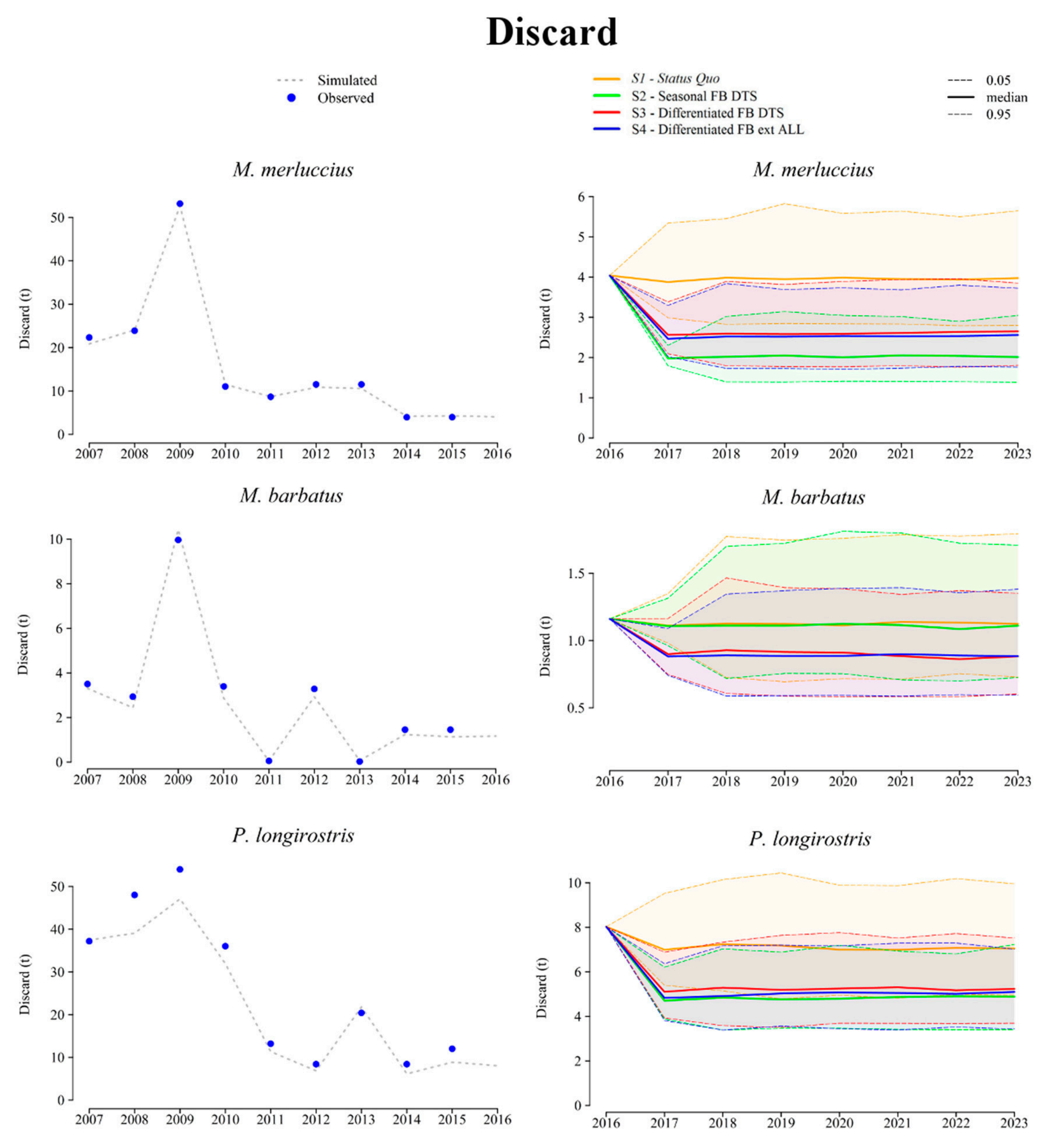

FIGURE 4 | Comparison among the scenarios of discards (trawlers) of European hake, red mullet, and deep-water rose shrimp in the hindcasting (2007–2016) and forecasting (2017–2023) timelines. Dotted line, Hindcasting from the bioeconomic modeling tool (BEMTOOL); Blue points, observed discard (DCF data).

conditions if it is not combined with a relatively low exploitation of immature fish. This has also been recently underlined in the Report of the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (ICES, 2015): "*There is a need to reduce fishing induced mortality on North Sea cod further, particularly for younger ages, in order to allow more fish to reach maturity and increase the probability of good recruitment.*"

The current technical regulations at the European Mediterranean level (EU, 2006) on the minimum landing size for a group of key species and the increase of cod-end mesh size to improve selectivity for trawlers do not seem sufficient to recover fish stocks from overexploitation [Scientific Technical and Economic Committee for Fisheries (STECF), 2016a; Cardinale and Scarcella, 2017], probably due to difficulties in the control procedures, as well as in the level of compliance. In addition, a positive effect of the landing obligation on this issue is quite uncertain so far. This paper made an effort in this direction by evaluating the effect of alternative management measures on the discards of the investigated species. Indeed, the additional protection in August implemented in S4 and the seasonal ban of IJ_DTS_VL1224—the second most important fleet segment in terms of capacity—in October decreased the discard volume

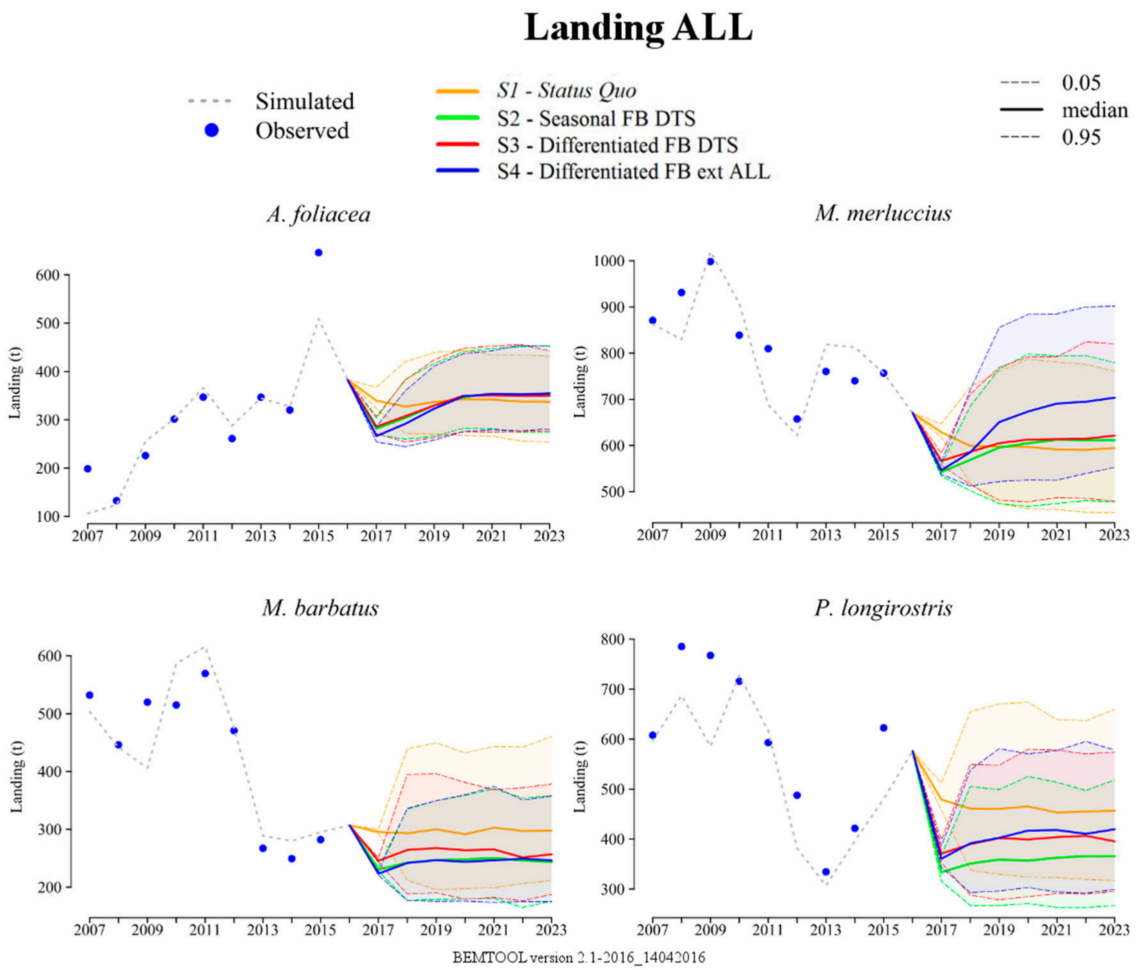

FIGURE 5 | Comparison among the scenarios of landings (all fleet segments) by target stocks in the hindcasting (2007–2016) and forecasting (2017–2023) timelines. Dotted line, Hindcasting from the bioeconomic modeling tool (BEMTOOL); Blues points, observed landing (DCF data).

of red mullet. In this month, there is still a high presence of the young-of-the-year of red mullet, given the effects of the already enforced seasonal fishing ban currently implemented in September.

The case study implemented in this paper is considered to be sufficiently representative of the demersal fishery in GSA 19, because it includes a consistent part of the fleet exploiting the demersal species in the area. In addition, the gears considered represent 62% of the total production in the area, and the target species—European hake, red mullet, deep-water rose shrimp, and giant red shrimp—make up 33% of demersal species' total landing. They are the targets driving the fisheries configuration in the area [Scientific Technical and Economic Committee for Fisheries (STECF), 2016a].

The landings forecasted in the *status quo*, maintaining the current exploitation pattern and fishing activity, were extremely consistent with historical data for all the examined species, returning 2023 landing volumes in line with the level observed in the last years of the time series. In contrast, the landings forecasted for 2023 for European hake were expected to decrease in comparison with those observed in the time series of the last years, thereby continuing the observed decline. Regarding the SSB, the *status quo* simulations showed a substantial increase only for giant red-shrimp in 2015, supported by a gain of the same magnitude in the observed landings of the same year. This relevant trend is due to the hefty 2013-year class (Mannini and Sabatella, 2015), confirmed even by the observations in the scientific trawl survey in the Mediterranean (MEDITS). Thus, for this species, the SSB projections exceed those of the time series due to the assumption of a stock recruitment relationship, represented by the geometric mean of the last 3 years (2013–2015) and influenced by the peak in recruitment observed in 2013.

For the other species, the SSB projections in the *status quo* are generally in line with the historical estimates of recent stock assessments. The lack of reliable stock recruitment relationships other than the geometric mean are generally mitigated by the timeline of the predictions in the designed scenarios and by the fact that the measures proposed and the introduced uncertainty are buffers against recruitment failures.

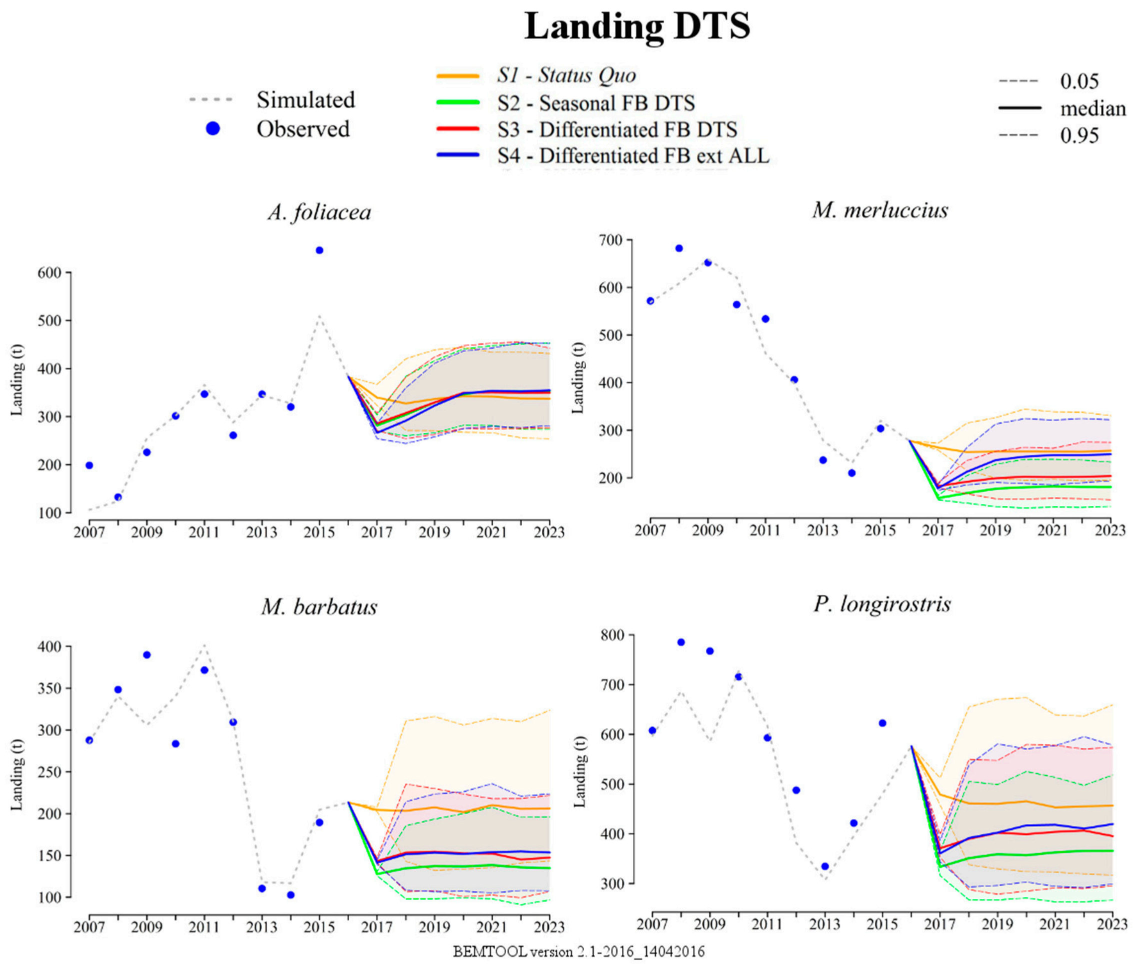

FIGURE 6 | Comparison among the scenarios of landings (trawlers) by target stocks in the hindcasting (2007–2016) and forecasting (2017–2023) timelines. Dotted line, Hindcasting from the bioeconomic modeling tool (BEMTOOL); Blues points, observed landing (DCF data).

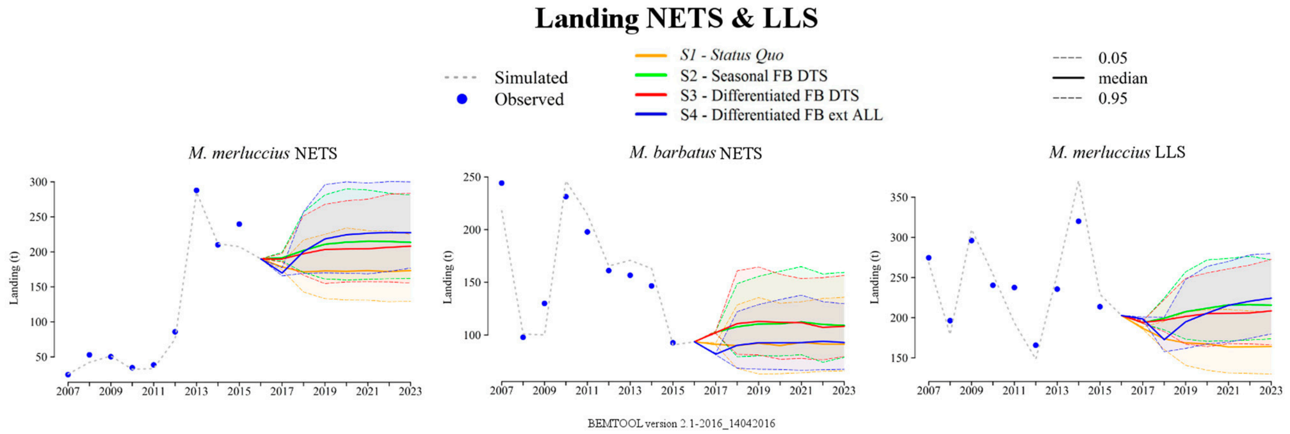

FIGURE 7 | Comparison among the scenarios of landings (nets and longlines) of European hake and red mullet in the hindcasting (2007–2016) and forecasting (2017–2023) timelines. Dotted line, Hindcasting from the bioeconomic modeling tool (BEMTOOL); Blues points, observed landing (DCF data).

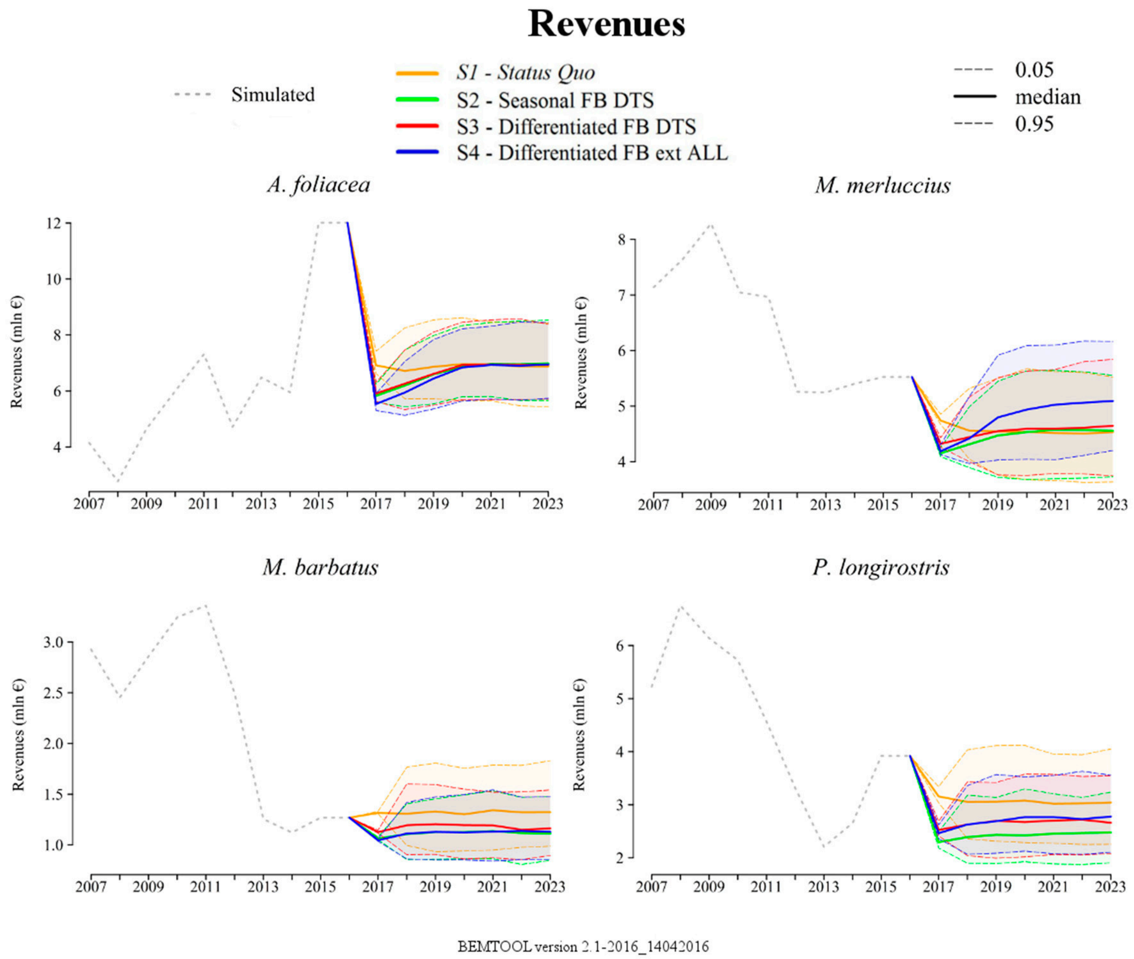

FIGURE 8 | Comparison among the scenarios of revenues (all gear) in the hindcasting (2007–2016) and forecasting (2017–2023) timelines. Dotted line, Hindcasting from the bioeconomic modeling tool (BEMTOOL).

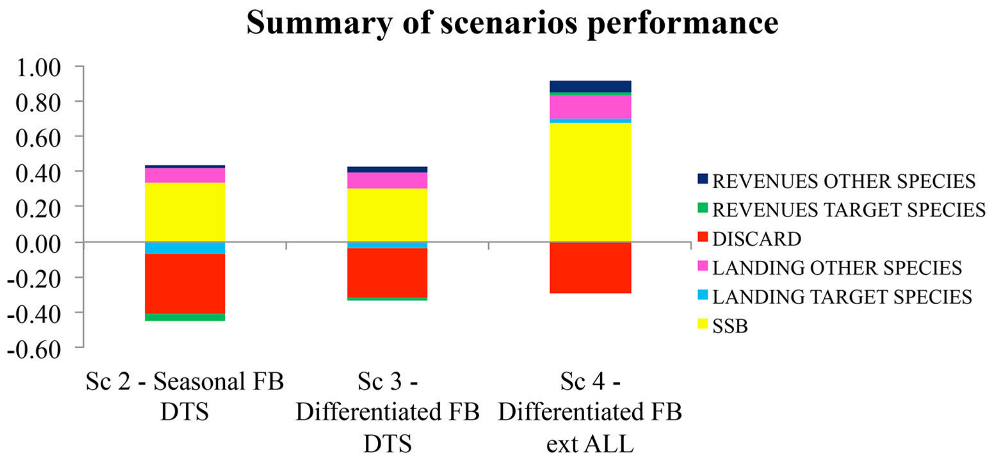

FIGURE 9 | Summary of the performance of the management scenarios compared to the *status quo* (difference in %) considering the following model-based indicators: spawning stock biomass (SSB), landing of target species, landing of other species, discards, revenues of target species, and revenues of other species.

The methods assume that the present bioeconomic conditions (recruitment, stock abundance, and fish prices) will not change substantially in 2017–2023, unless they change due to the designed management measures. Full compliance with such measures is also assumed, and the reduction in fishing effort is linearly translated into a reduction in fishing mortality (lacking other complementary information), under the assumptions of nearly constant or randomly varying catchability according to time but varying catchability among the fleets. Furthermore, the modeling exercise did not consider some possible rearrangements of fleets in terms of both absolute size and relative presence of each gear.

The scenarios designed were specifically conceived to protect juveniles of the exploited populations both in space and time, considering both the recruitment time and the exploitation pattern of the vessels fishing in the different fishing grounds. The alternating fishing ban (Dunn et al., 2011; Rassweiler et al., 2012; Russo et al., 2014b; Plagányi et al., 2015) can be considered a management strategy that, given a feasible control in the harbors—as for the seasonal fishing ban—could efficiently change the exploitation pattern, thereby redirecting the fishing activity toward biggest individuals and making the harvest strategy more viable. Indeed, this alternating fishing ban could produce a less severe impact on landings and revenues than the seasonal fishing ban does, while having almost the same effect on the improvement in the SSB and reducing the proportion of smaller individuals, which are less profitable in the market. Indeed, Beverton and Holt's paradigm calls for fishing across the widest possible ranges of species, stocks, and sizes in an ecosystem, in proportion to their natural productivity (Garcia et al., 2012), the so-called balanced harvesting (Zhou et al., 2010; Garcia et al., 2012; Rochet et al., 2013). Balanced harvesting, in line with EAFM, aims to minimize the effects of fishing on marine fish communities and ecosystems by protecting juvenile fish from fishing and taking adults in proportion to their productivity (Jacobsen et al., 2013). In other words, moderate fishing rates addressing more productive cohorts would relax the impact on the population size structure and lead to higher yields (Froese et al., 2008). Nevertheless, no attempt has been made so far to disentangle the effects of fishing mortality and minimum size limits on the size structure of an exploited population (Froese et al., 2016). The present work contributes in this direction, given that fishing effort reduction was modeled using the time of offspring occurrence as a driving factor in establishing fishing closure. This was possible given the flexibility of the bioeconomic model, which allows a parameterization in the biological core model at the month scale.

Here, fleet performances were evaluated only in terms of revenues, which are considered a meaningful indicator representing the socioeconomic consequences of the different scenarios in a relatively complete way. This because the fleet of each harbor operates in the nearest portion of shelf and/or slope, and thus the costs (variable, fixed, capital, and labor) are also equivalent in the implemented management measures.

According to Spedicato (2016), in GSA 18 (contiguous to GSA 19), the costs (summing up fixed, variable, capital, and labor costs) supported by trawlers between 12 and 18 m are, on average (2008–2014), 74% of the total revenues, while for longlines, they are about 63%, and for small-scale fishery they are about 86%. The fixed costs sustained by vessels independently from the fishing activity (administration, obligatory insurance, fishing license, harbor charges, etc.) were reported to be about 4%, while the labor cost was about 25%, and the variable costs were about 35%. The same percentages can be reasonably assumed to be supported by the GSA 19 fleet.

In the proposed scenario, vessel owners should support the fixed, capital, and investment costs entirely. However, applying the explored management measures, revenues similar to the historical values for GSA 19 are expected; this is because, in the future, the fleets may be able to reach or even exceed the current level of profit. This may counterbalance the risk of underutilization for some stocks.

Indeed, as shown by the present study, the remarkable benefit obtained for European hake stock, as well as the increase of the overall landing in S4 scenario, compensates for the slight underutilization of red mullet and deep-water rose shrimp. This is the consequence of a combination of several factors, such as the life history traits of these species (faster growth rates, shorter lifespans) and an exploitation pattern that is less affected by the occurrence of small individuals for the species.

There is an urgent need for management measures in addition to those currently in place to avoid a further deterioration of the productivity of the stocks being overexploited (e.g., fishing mortality of hake largely exceeding the reference point; FAOSAC, 2015). This is also important because landings of key species are in sharp decline, while the fishing effort appears slightly reduced.

The results of this study, although obtained using a simulation-based approach, clearly confirmed that significant improvements of stock conditions could be achieved by protecting critical life stages through the fishing bans of well-defined areas and times. Future developments of this work could address the exploration of alternative scenarios related to changes in fleet capacity (i.e., fleet segment size) and/or technical aspects of gears that influence selectivity. Furthermore, it could be interesting and potentially useful to set up a roadmap based on stakeholder involvement to identify shared scenarios to be evaluated (e.g., Lembo et al., submitted). This could guarantee more reliable advice for the management bodies, even supporting the participative component that represents another key aspect of the new CFP.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fmars.2017.00193/full#supplementary-material

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North East Atlantic vs. Mediterranean Marine Protected Areas as Fisheries Management Tool

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The effectiveness of management initiatives implemented in the context of the European Common Fisheries Policy has been questioned, especially with regard to the Mediterranean. Some of the analyses made to compare the fishing activity and management measures carried out in the North East Atlantic and in the Mediterranean do not take into account some of the differentiating peculiarities of each of these regions. At the same time, they resort to traditional fisheries management measures and do not discuss the role of marine protected areas as a complementary management tool. In this respect, the apparent failure of marine protected areas in the North-East Atlantic compared with the same in the Mediterranean is challenging European fishery scientists. Application of the classical holistic view of ecological succession to the functioning of fishery closures and no-use areas highlights the importance of combining both management regimes to fully satisfy both fishery- and biodiversity-oriented goals. We advocate that an optimal management strategy for designing an MPA to protect biodiversity and sustain fishing yields consists of combining a network of no-use areas (close to their mature state) with fish boxes (buffer zones maintained by fishing disturbance in a relatively early successional stage, where productivity is higher), under a multi-zoning scheme. In this framework, the importance of no-use areas for fisheries is based on several observations: (1) They preserve biological diversity at regional scale, at all levels—specific, habitat/seascape, and also genetic diversity and the structure of populations, allowing natural selection to operate. (2) They permit the natural variability of the system to be differentiated from the effects of regulation and to be integrated in appropriate sampling schemes as controls. (3) They maintain the natural size and age structure of the populations, hence maximizing potential fecundity, allowing biomass export to occur from core to regulated areas, dampening the fluctuations derived from deviations from the theoretical optimal effort in the fishing zone.

Keywords: North East Atlantic, Mediterranean, Marine Protected Areas, fisheries, management

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INTRODUCTION

The effectiveness of management initiatives implemented in the context of the European Common Fisheries Policy (CFP), operative since 1984, has been put into doubt and the fisheries management system in Europe has been strongly criticized (Froese, 2011a,b). Immediately, providing data on the evolution of some traditional fisheries, Cardinale (2011) countered those claims. Since then, attention has focused particularly on the situation in the Mediterranean Sea, where the alarming decline of its fish stocks is a matter of increasing concern (Vasilakopoulos et al., 2014; Cardinale and Scarcella, 2017). This is especially evident when comparing the effectiveness of fisheries management in the North East Atlantic and the Mediterranean. According to these reviews, NE Atlantic fish stocks have been gradually recovering as a result of the decrease in fishing pressure following implementation of the EU's CFP during the past decade (Cardinale, 2011), while European Mediterranean fish stocks seem to be out of control, and regulations are often poorly enforced (Vasilakopoulos et al., 2014; Cardinale and Scarcella, 2017).

Most of the above mentioned analyses focus on stocks caught by trawlers and purse seines, both characteristic of open waters and relatively deep bottoms, and propose management actions based on traditional fisheries management tools consisting of limiting juvenile exploitation, harvesting species a few years after maturation, and changes in selectivity and exploitation rates (Selig et al., 2017). It is expected that these measures should maximize long-term yields and halt stock depletion (Hilborn and Ovando, 2014), and are in accordance with the EU's CFP, which requires that fish stocks should be exploited at a level that generates the maximum sustainable yield (MSY; European Commission, 2006; Vasilakopoulos et al., 2014).

However, Mediterranean and North East Atlantic regions differ in oceanographic and climatic processes, human impacts, cultural heritage, spatial scales and heterogeneity and size of habitats and populations, that condition the nature of the fisheries (Smith and Garcia, 2014). Therefore, any proposal to improve management strategies should consider other complementary actions, especially taking into account that local, small-scale, coastal, artisanal fisheries constitute an important component of the idiosyncrasy of Mediterranean fisheries. Neither should it be forgotten that an important contribution of this fishing activity is developed in coastal lagoons where stock dynamics and the characteristics of the fishing gears used are difficult to incorporate in traditional approaches to fishing management (Pérez-Ruzafa and Marcos, 2012).

One aspect not explicitly considered in the above mentioned reviews (Vasilakopoulos et al., 2014; Cardinale and Scarcella, 2017) and that should be taken into account is that, after the failure of traditional fisheries management measures (Waters, 1991), marine reserves have been strongly advocated as an ideal tool for the management of coastal fisheries (Plan Development Team, 1990; Roberts and Polunin, 1991; Dugan and Davies, 1993; Agardy, 1994; Gerber et al., 2002). Indeed, analysis of global trends in world fisheries points to the urgency of implementing non-conventional approaches, including the establishment of marine reserves, which enabled the apparent sustainability of pre-industrial fisheries (Pauly et al., 2005). As a result, a large number of marine protected areas (MPAs) have been established in recent decades throughout the world, including the EU (Jones et al., 1993; Lubchenco et al., 2003; Fenberg et al., 2012; Devillers et al., 2015; Batista and Cabral, 2016). Beyond this, "the establishment of MPAs is an important contribution to the achievement of a good marine environmental status" under the European Marine Strategy Framework Directive (Directive 2008/56/EC) and are considered an affordable way to mitigate and promote adaptation to climate change (Roberts et al., 2017).

Formally, the terms marine protected area (MPA) and marine reserve are not exactly synonymous (**Table 1**) and, in fact, there are a large number of conservation entities, with different levels of protection, permitted uses, and management measures.

As a fisheries management tool, a marine reserve is a no-take zone where it is forbidden to extract organisms in any way, except, in some cases, when required for scientific monitoring (Roberts and Hawkins, 2000; Halpern and Warner, 2002).

For its part, the term MPA is a more general concept applied to defined geographical areas, which are recognized, and managed, by law or other effective regulations, to preserve marine ecosystems and their associated ecosystem services and attributes, including biodiversity, species populations, cultural values, or economic resources such as fisheries production (Dudley, 2008; Thomas et al., 2014). Such areas can take a high variety of forms and designs (Planes et al., 2006), denominations (http://oceanservice.noaa.gov/facts/mpa.html), accepted uses (Mazor et al., 2014b) and management objectives at all levels of government and spatial scales (Portman et al., 2012; Giakoumi et al., 2013). In the UK, for example, MPAs include Special Areas of Conservation according to the EU Birds and Habitats Directives, Marine Nature Reserves' and Sites of Special Scientific Interest, the main aim of most of them being conservation of biodiversity, while very few are designed for managing fisheries (Gubbay, 2006). Indeed, throughout the world, the vast majority of MPAs allow fishing and extractive activities, as well as other commercial or recreational practices such as boating or scuba-diving (Thomas et al., 2014).

Despite this multiciplity of objectives, MPAs are viewed in Europe and worldwide as the best way to protect fishing resources and conserve marine biodiversity (Gaines et al., 2010a; Costello and Ballantine, 2015; Lubchenco and Grorud-Colvert, 2015). Many European MPAs have a common objective to keep harvested populations below the overfishing threshold, while maximizing sustainable yields (Fenberg et al., 2012; European Environment Agency, 2015), a second objective being to prevent the loss of biodiversity due to human erosion (Pauly et al., 2002, 2005).

The expected benefits of MPAs include preserving the spawners and the natural size and age structure of populations, maintaining assemblage structure and ecosystem equilibrium, maintaining genetic diversity and facilitating the recovery of stocks in over-exploited areas through the exportation of eggs and larvae to neighboring areas. At the same time they allow the development of research in non-impacted ecosystems that can be used as control areas in experimental sampling designs and as reference conditions for environmental impact and ecological status assessments (García-Charton et al., 2008; Wood et al., 2008; Lester et al., 2009; Fenberg et al., 2012).

Here (1) we provide a comprehensive review of the effects of MPAs as a fisheries management tool, (2) we highlight the differences in their use and expected benefits between Northeastern and Southern-Mediterranean- Europe, and (3) we apply the classical holistic view of ecological succession to the

TABLE 1 | Definitions of the most common existing figures and terminology for the protection of marine areas.

Key term	Definitions
Marine Protected Area	The IUCN, after the more specific initial definition (IUCN, 1988, 1994), actually aligns the meaning of MPA with the definition of a "protected area" as "a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (Dudley, 2008). More concretely, Marine Protected Areas (MPAs) are "any marine area set aside under legislation to protect marine values". Such values include conservation, commercial, species enhancement, scientific importance, historic, recreational, scenery or aesthetics, cultural, etc. (Day and Roff, 2000). "They come in a variety of forms and denominations, as marine sanctuaries, marine reserves, fully protected marine areas, no take zones, estuarine research reserves, ocean or marine parks, or marine wildlife refuges, which may have different implications according to the country in which they are established" (FAO, 2011; http://oceanservice.noaa.gov/facts/mpa.html).
Multiple-use MPA	"MPAs typically comprise fluid and dynamic marine ecosystems, have a high diversity of habitats and species within an area and contain highly migratory marine species. This complexity often dictates the need for multiple objectives and complex management schemes" (Dudley, 2008). In the marine environment, this is particularly important and zoning is recommended in the IUCN best practice guidelines on MPAs as the best way of ensuring protection and managing multiple-use protected areas (Kelleher, 1999).
Marine Reserve	"Marine reserves are a specific type of MPA that achieves the preservation of the biodiversity and other values in a strictly protected area, where activities that remove animals and plants or alter habitats are prohibited, except as needed for scientific monitoring. They have become an important tool for both marine biodiversity protection and fisheries management" (Roberts and Hawkins, 2000; Dudley, 2008; http://www.protectplanetocean.org/introduction). A marine reserve or "no take" MPA is a highly protected type of MPA where removing or destroying natural or cultural resources is prohibited. (NOAA access 06/06/2017 http://marineprotectedareas.noaa.gov/aboutmpas/). "They usually allow human access and even some uses, but prohibit the extraction or significant destruction of natural and cultural resources. Also coincide with the no-take level of protection established in some whole or multiple-use MPAs, and so they are often called a "no-take" MPA" (http://marineprotectedareas.noaa.gov/pdf/helpful-resources/factsheets/mpa_classification_may2011.pdf; http://www.protectplanetocean.org/collections/introduction/introbox/reserves/introduction-item.html).
No-Take zone	"This protection category is not compatible with any removal of marine species or modification, extraction or collection of marine resources, with scarce exceptions such as scientific research. Human visitation is limited, to ensure preservation of the conservation values. Setting aside strictly protected areas in the marine environment is of fundamental importance, particularly to protect fish breeding and spawning areas and to provide scientific baseline areas that are as undisturbed as possible. They may comprise a whole MPA or frequently be a separate zone within a multiple-use MPA, seen as "cores" surrounded by other suitably protected areas" (Dudley, 2008).
Buffer zone	"Areas around a core protected zone that are managed to help maintain protected area values" (Dudley, 2008). They preserve the entire protected zone from potentially damaging external influences and are essentially transitional areas where appropriate economic activities are permitted and where sustainable resource management practices can be developed (Bennett and Mulongoy, 2006; Dudley, 2008).
Fish Box	"Some sites, such as fish spawning aggregation areas or pelagic migratory routes, are critically important and the species concerned are extremely vulnerable at specific and predictable times of the year, while for the rest of the year they do not need any greater management than surrounding areas. The EU has encouraged the establishment of such conservation "boxes" or "fishery closure areas" within which seasonal, fulltime, temporary or permanent controls are placed on fishing methods and/or access" (Dudley, 2008; http://www.protectplanetocean.org/introduction/introbox/glossary/glossary/introduction-item.html#marres).
Network of MPAs	"Set of discrete MPAs within a region or ecosystem that are connected through complementary purposes and synergistic protections, at various spatial scales, and with a range of protection levels designed to meet objectives that a single reserve cannot achieve. A network of MPAs could focus on ecosystem processes, certain individual marine species, or cultural resources. For example, an ecological network of MPAs could be connected through dispersal of reproductive stages or movement of juveniles and adults" (IUCN-WCPA, 2008; http://www.protectplanetocean.org/introduction/introbox/glossary/glossary/introduction-item.html#marres). Connectivity and its scales play here a relevant role.

functioning of fisheries closures and no-use areas, in order to put light into this debate.

A POWERFUL MANAGEMENT TOOL FOR BIODIVERSITY CONSERVATION

The effects of protection on fish structure inside reserves have been demonstrated in numerous studies (e.g., McClanahan and Mangi, 2000; Claudet et al., 2008, 2010; García-Charton et al., 2008; Lester et al., 2009; Guidetti et al., 2014; Sciberras et al., 2015), although there are still several aspects that need confirmation and further efforts must be made to understand the complex mechanisms and processes that clearly produce positive effects in some cases and negative or neutral effects in others (Gaines et al., 2010a; D'agata et al., 2016; Gill et al., 2017). Basically, MPAs are expected to protect critical spawning stock biomass of species from fishery-related depletion (Bell, 1983; García-Charton et al., 2004; Claudet et al., 2006), so that they recover and maintain a natural size and age structure in the populations, hence maximizing potential fecundity, allowing biomass exportation from core to regulated areas (Reñones et al., 1999; Goñi et al., 2003; Brito et al., 2006; Harmelin-Vivien et al., 2007; Dimech et al., 2008; Hackradt et al., 2014; Di Lorenzo et al., 2016). They also reestablish ecological interactions (Guidetti, 2006a,b) and preserve biological diversity at a regional scale (but see Klein et al., 2015) at all levels—specific, habitat/seascape, and also genetic diversity and populations structure (Pérez-Ruzafa et al., 2006)—, allowing the force of natural selection to operate.

These effects can take place in a relatively short time. In a review of 80 reserves, Halpern and Warner (2002) found that most assemblage descriptors, such as diversity, density, average organism size, and biomass inside the reserves, reach levels comparable to control areas within the first 1–3 years and are maintained in reserves for up to 40 years. Other empirical studies show that the time taken to detect the first direct effects on target species is around 5 years, while the detection of indirect effects on other taxa takes 10–15 years (Babcock et al., 2010) or more (Claudet et al., 2008), a significantly longer time but still short enough to be perceived at the scale of human perception of changes, and within the 5–20 years time-horizons used in cost-benefit analysis or community planning (Tonn et al., 2006; Hunt and Taylor, 2009; Pahl et al., 2014).

MPAS AS FISHERIES MANAGEMENT TOOL

The interest of MPAs as fishery management tool lies mostly on their potential to improve artisanal fisheries of high-value species in surrounding fishing grounds (Kerwath et al., 2013; Di Franco et al., 2016; Lloret et al., 2017). At the same time, they intend to favor the economic development of the area through the establishment of services related to tourism and diving activities providing an alternative source of inputs also for fishermen (Angulo-Valdés and Hatcher, 2010; Rees et al., 2015; Pascual et al., 2016). The key question for fisheries management is whether MPAs are effective only inside the protected area or whether they are also useful for maintaining productivity in the surrounding exploited grounds.

MECHANISMS OF EXPORTATION

Marine fish dispersal that would benefit fisheries in the vicinity of an MPA may occur via several mechanisms: egg and larval dispersal (Cowen et al., 2000; Abesamis et al., 2016, 2017), the trophic or reproductive migrations of adults (Green et al., 2015), nomadic or ontogenetic movements (Grüss et al., 2011), and, density-independent, home-range movements by individuals across reserve boundaries and home-range relocation because of density-dependent factors (Rakitin and Kramer, 1996; Russ and Alcala, 1996; Kramer and Chapman, 1999; Pérez-Ruzafa et al., 2008). Although, all these mechanisms potentially increase the catch in surrounding areas, and hence likely benefit fisheries by helping to recover and maintain target populations, full benefits of MPAs would require protecting also other mechanisms determining reproductive success, such as those necessitating essential habitats (Elliott et al., 2016)—e.g., spawning grounds (Erisman et al., 2015; Sadovy de Mitcheson, 2016) and recruitment areas (Cheminée et al., 2017). On the other hand, some authors differentiate "ecological spillover" (i.e., the net export of juvenile, subadult and adult biomass from MPAs outwardly driven by density-dependent processes) from "fishery spillover" (i.e., the proportion of this biomass that can be fished, taking into account regulations and accessibility; Di Lorenzo et al., 2016).

Although, some of these processes are difficult to demonstrate in the field (Harmelin-Vivien et al., 2008; Lester et al., 2009; Di Lorenzo et al., 2016), the ability of MPAs to improve adjacent fisheries has also been related to indirect evidence, such as spatial redistribution of fishing effort (Murawski et al., 2005; Goñi et al., 2008; Stelzenmüller et al., 2008; Cabral et al., 2016) and the direct recording of catches by commercial fishing (Vandeperre et al., 2011).

In the last decade, modeling approaches have also analyzed the exportation of individuals on the basis of diffusive processes dependent on density gradients (Gerber et al., 2003; Neubert, 2003; Kellner et al., 2007; Pérez-Ruzafa et al., 2008), which is consistent with observed patterns in fish abundance and fishing effort distribution. Other models incorporate movement patterns—migration, ontogenetic movements, etc. (e.g., as those reviewed by Grüss, 2014).

Protection also produces a rapid response in fishermen's behavior. From the first year, fishing effort and "catch per unit effort" (CPUE) tend to concentrate at the boundaries of the MPAs and gradually increase with time. Using a meta-analytical approach to investigate the effects of protection on adjacent fisheries based on 28 data sets from seven southern European MPAs, Vandeperre et al. (2011) found clear effects on the surrounding fisheries, both as regards the CPUE of the target species and, especially, on the CPUE of the marketable catch.

These effects mainly depend on the time of protection and on the size of the no-take area. The CPUE of both the marketable catch and target species increased gradually by 2–4% per year over a long period (at least 30 years). On average, the protected areas provided catches about 2.4 higher than those from the non-protected areas (Vandeperre et al., 2006).

Despite this quick response, the effects can be hidden by fishermen's behavior. Up to 75% of fishing gears can be deployed within 1 km of the MPA (Murawski et al., 2004, 2005) and most catches in other studies were concentrated within 10 km from the reserve boundaries (Kellner et al., 2007; Goñi et al., 2008; Stelzenmüller et al., 2008). The rapid concentration of fishing effort near the boundaries of the reserve causes a rapid fall in CPUE (Pérez-Ruzafa et al., 2008; Vandeperre et al., 2011), so that a successive increase/decrease/recover of yields ultimately leads to pre-reserve levels being exceeded (Hopf et al., 2016). However, in very small MPAs or when the protected area is located peripherally within the metapopulation, the recovery time runs from several years to decades and reserves are sometimes unable to support the increased mortality so that the metapopulation collapses (Hopf et al., 2016).

Although, some empirical studies showed that the spatial response of fishing boats to the implementation of an MPA greatly depends on the local particularities (fishing modalities, spatial distribution of habitats, prevailing winds, currents regime, etc.), precluding an oversimplified assumption about redistribution of fishing effort (Cabral et al., 2016), usually, the relocation of fishing effort leads to a "fishing the line" harvesting tactic (Kellner et al., 2007).

WHO BENEFITS MOST FROM MPAS?

MPAs are not only a good fisheries management tool. The economic revenues of MPAs have been claimed as being beneficial for all stakeholder groups, especially in southern European MPAs, where the demand for diving activities increases exponentially and fishing and scuba-diving are the main coexisting uses (Roncin et al., 2008; Fenberg et al., 2012; Sala et al., 2013). A broad socio-economic field survey covering 12 case studies in southern Europe showed a variety of situations, from MPAs where commercial fishing is the major economic stake (up to 88% of total incomes locally generated by fishing and diving), to MPAs where recreational activities have a dominant economic role (where incomes generated by commercial fishing can amount to <5% of the money generated by scuba diving; Roncin et al., 2008). In general, recreational diving is prevailing in coastal areas, while fishing is more associated with MPAs far from the coast, where diving activities are difficult (Roncin et al., 2008). On average, the amount of locally generated income by fishing and diving in the southern European MPAs studied by Roncin et al. (2008) represented at least 2.3 times the management costs.

According to Mangi and Austen (2008), there is a high level of satisfaction among users of marine reserves. However, most stakeholders consider MPAs that have been established for longer periods of time offer greater benefits for conservation than fisheries and that such conservation benefits gradually increase with the time of protected area management. Of note is the fact that the main reasons given by divers to justify the use of MPAs as diving sites are fish abundance and the presence of some spectacular or "emblematic" species (e.g., grouper in the Mediterranean). However, the evaluation of MPAs as areas to benefit fisheries decreased with the time an area is protected due to a gradual change in fishermen's perception.

The belief amongst fishermen in the potential of MPAs to deliver fisheries objectives declines with time, coinciding with the time taken by the relocation process of fishing effort to reach a "fishing the line" equilibrium. After this time, all fishermen in a gradient from the MPA boundary would attach the same CPUE, explaining why after this time the perception of fishermen could become more neutral, while the perception of benefits for divers and diving operators is still increasing.

FISH BOX VS. MPAS

Despite the benefits provided by marine reserves, after more than 25 years of research into their effectiveness, fishery managers question European scientists about the apparent failure of north European MPAs to reach the expected fisheries objectives (Pastoors et al., 2000; Daw and Gray, 2005; Beare et al., 2010). Moreover, if we compare them with Mediterranean MPAs, which are generally viewed by researchers and, more importantly, by users as being successful (Guidetti et al., 2014), the question arises as to the possible causes of such divergence.

In classical fisheries science, it is increasingly assumed that the concept of MSY, as a reference for the catch rate, should be reinterpreted as an upper limit rather than a management target, by replacing the traditional goal of maximizing the catch by that of maximizing economic profit or even minimizing the impact of fishing (Froese et al., 2011, 2016a,b), although this is not being implemented yet in national and EU fishing policies (Marchal et al., 2016). This requires the introduction of a range of management tools that permits an overall reduction in exploitation rates. Implementing the best management tools may depend on the local context, but there is an overall view that a combination of traditional fisheries management measures (catch quotas, closed seasons, community management) coupled to strategically placed fishing closures, ocean zoning, increased selectivity of fishing gear, and economic incentives, holds much promise for the restoration of marine fisheries and ecosystems (Worm et al., 2009; Froese et al., 2015). In theory, except for sedentary species, for which reserves have important advantages, the management of fisheries through setting up reserves and management through effort control may produce identical yields under a reasonable set of simplifying assumptions corresponding to a broad range of biological conditions (Hastings and Botsford, 1999).

In Europe, MPA design differs between Atlantic and Mediterranean areas (**Figure 1**). Northern MPAs (the so-called fish boxes or fisheries closures; Pastoors et al., 2000) are generally very large (hundreds of thousands of hectares), and are intended to protect one or a few target or by-catch species (e.g., plaice, sole, cod, herring, sprat, haddock). In this case, fisheries regulations typically consist of traditional fishing regulations, banning specific gears, and/or reducing the fishing effort within the whole closed area. For their part, Mediterranean MPAs (Planes et al., 2006; Fenberg et al., 2012) are usually small (hundreds of hectares or less; Gabrié et al., 2012; Portman et al., 2012), and are in general located in areas that are biologically unique, because of the occurrence of remarkably diverse and/or complex habitats; they always include a core marine reserve, a no-use or no-take area (i.e., where all human activity is banned or any type of fishing is absolutely prohibited), and they are often bounded by a buffer area, where some fishing activity is allowed and strongly regulated by traditional approaches. Although, the difference in total size arises as the immediate option to explain differences between Northern and Southern European MPAs, empirical evidence is less clear on this: while some studies argue for large MPAs to ensure their success, other recommend smaller MPAs (Claudet et al., 2008; Fletcher et al., 2015; Hughes et al., 2016).

The proponents of an ecosystem approach to fisheries management are still struggling with finding practical ways of application (Fulton et al., 2014; Jennings et al., 2014; Link and Browman, 2014; Berg et al., 2015; Coll et al., 2015; Long et al., 2015; Patrick and Link, 2015). Most initiatives so far are based on the notion that less diverse communities are less productive (Gamfeldt and Hillebrand, 2008; Tilman et al., 2014; Strong et al., 2015). But, as Margalef (1997) pointed out [embracing Odum (1969) holistic view of succession], decreasing productivity to biomass ratios is the most likely driver of ecosystem growth when moving from early to more mature stages, once an initial "squandering" phase has been surpassed (**Figure 2**). This pattern generally does not take into account the mechanisms determining the actual sequence of replacement and the rate

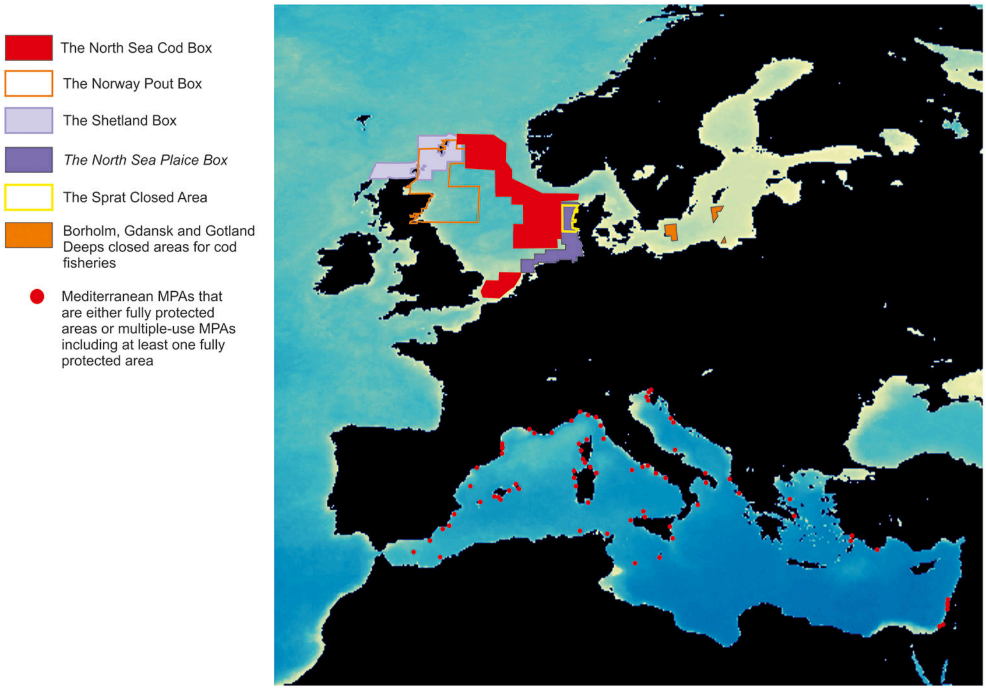

FIGURE 1 | Main fish closures in the North and Baltic Seas (Sørensen, 2006) and distribution of present Mediterranean MPAs in April 2017 (MAPAMED, 2017; http://www.medpan.org/en/mapamed). Base map corresponds to averaged maximums of Chlorophyll a for the period 2003–2010 from satellite data.

of the same (Valiela, 1995). In this context, the objectives of fishery measures of maintaining a MSY, which are those of most Northern MPAs, can only be attained in a relatively early phase of succession, when net production is maximized (**Figure 2**). The position of this stage in the succession will vary depending on the life cycle, trophic level or life-history strategy (*r* vs. *K*) (or, more generally, the average trophic level) of the species forming the catch. But this situation is achieved in a narrow successional fringe-, so that overexploitation will lead to a decrease in productivity, although the same occurs if regulatory measures move the ecosystem excessively toward more mature stages. The latter situation leads to the apparent paradox that, contrary to expectations, fishing limitations reduce fishing yields in fish boxes when more harvested (i.e., stressed by fishing disturbance, and then kept at a younger successional stage) are compared with partially protected areas, making the failure of protection measures more probable.

By contrast, Mediterranean MPAs enhance fishing yields through spillover from core no-take areas to neighboring, regulated and unprotected areas (Gell and Roberts, 2003; Tudela et al., 2005; Stelzenmüller et al., 2008) after the protected ecosystem is left to reach a state of maturity (**Figure 2**). A late successional stage is characterized by more species, longer-lived organisms, and complex food webs with a higher number of trophic levels. This mature stage is inevitable, as succession is a process of self-organization (Fath et al., 2004). Empirical studies in Mediterranean MPAs (García-Charton et al., 2004; Tudela et al., 2005; Coll et al., 2013; García-Rubies et al., 2013; Guidetti et al., 2014) showed how fish communities undergo a huge increase in target biomass—usually piscivore species within core marine reserve areas, and restoring a more "natural" community structure, provided that they are well enforced (Guidetti et al., 2008; Di Franco et al., 2016). All this leads to the general view that Mediterranean MPAs are almost always successful in achieving the planned objectives.

The above holistic ecological considerations lead us to advocate that an optimal management strategy for designing an MPA (also in the Northern Atlantic) to protect biodiversity and sustain fishing yields would be a combination of a network of no-use marine reserve areas (close to their mature state) with fish boxes (maintained by fishing disturbance in a relatively early successional stage, where productivity is higher), under a multi-zoning scheme.

OPTIMUM DESIGN: MAXIMIZING CONSERVATION, EXPORTATION AND MAINTENANCE COSTS

Zonation in an MPA

There is no one design for an MPA. Apart from the size and form, some MPAs consider only a no-take zone or marine reserve where no human activity except scientific surveys is forbidden, others also include one or several buffer zones with different relative sizes with respect to the core reserve where some gears and different degrees of regulated fishing is permitted, and other buffer zones are entirely regulated like the fish box (Planes et al., 2006; Horta e Costa et al., 2016).

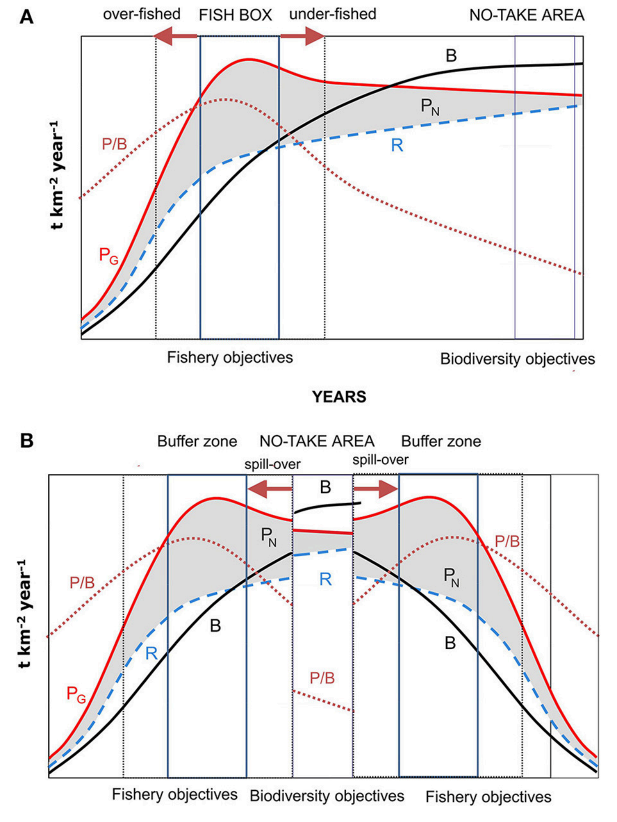

FIGURE 2 | (A) Energetic of succession in an ecosystem. P_G, gross production; P_N, net production; R, total community respiration; B, total biomass; P/B, productivity (Modified from Odum's, 1969). The fishing activity (and the objectives of fish boxes) focuses on the early stages of ecological succession, where net production is maximum. But any deviation from the optimum of fishing pressure moves the ecosystem to stages with lower net production. By contrast, conservation objectives focus on late stages, where maximum biomass is reached and the ecosystem reaches maturity and complexity, but net exploitable production is minimal. **(B)** Southern European MPAs have a central no-take area whereby ecological succession leads the ecosystem to maturity, flanked by buffer zones managed like the fish box. The export of biomass from the no take area to the buffer zone dampens the catch fluctuations derived from deviations from optimal effort in the fishing zone.

The design affects MPA effectiveness and, contrary to what might be expected, larger buffer areas seem to negatively affect both ecological aspects and fishing yields in the surrounding areas (Claudet et al., 2008; Vandeperre et al., 2011). Although, no explanation has been proposed for this, it could be related to the fact that the spill-over spatial scale is much reduced. Enlarging the buffer area implies that, although subjected to fishing regulations, the real effects of protection due to the no take zone became diluted in a longer gradient, making differences between the buffer and the free fishing areas less pronounced than with smaller buffer zones.

How Big Should an MPA Be? Size Do Matter But…

Meta-analyses performed on 58 datasets from 19 Southern European MPAs showed that the size of the no-take zone and time of protection are the main factors determining the effectiveness of an MPA for preserving the abundance and size structure of fish assemblages (Claudet et al., 2008). Similar conclusions are reached when the effects on fisheries are analyzed considering CPUE data (Vandeperre et al., 2011).

Pérez-Ruzafa et al. (2008), using a modeling approach, showed that medium size to large marine reserves (>600 ha) are to be preferred to small ones, both to maximize the protection of fish populations abundance and to improve the exportation of biomass across the marine reserve boundaries (Pérez-Ruzafa et al., 2008), thus agreeing with empirical data. Larger reserves attain between 80 and 100% of the carrying capacity in the first 5 years after protection depending on fish mobility or fishing effort in the surrounding area. However, reserves smaller than 500 m in radius have difficulties in attaining 50% of the carrying capacity, especially in the case of fishes of high mobility and subject to high fishing effort in neighboring areas (Pérez-Ruzafa et al., 2008). Furthermore, improvement in maintaining higher populations abundance or in exporting individuals increase very slowly for reserves larger than 1,500 ha (Pérez-Ruzafa et al., 2008).

The spatial scale of influence of a marine reserve is lower than might be expected. Some reviews of demersal fish and invertebrates suggest adult neighborhood sizes ranging from a few kilometres to 10 to 100 km, and for larval dispersal, of 10 to 100 km for invertebrates and 50 to 200 km for fish (Palumbi, 2004). Recent studies (e.g., D'Aloia et al., 2015; Green et al., 2015) reports even shorter average dispersal distance (<5–15 km) and highlight that self-recruitment is a common phenomenon. Field studies based on underwater visual censuses have shown that the gradient in fish abundance due to spill-over through the reserve boundary is only detectable at small spatial scales (a few 100 m; Harmelin-Vivien et al., 2008). In modeling approaches, the effect of the flux of individuals from the reserve to the fished areas is evident at <5–10 km from the boundary (Pérez-Ruzafa et al., 2008). In the case of larvae, Jessopp and McAllen (2007) found limited exchange between reserve and non-reserve areas at a relatively small spatial scale (<3 km) depending on the hydrographic and geomorphologic characteristics of the sites. In the case of models for larval exportation, changes in yield biomass during the first year are evident within 14 km of the reserve (Hopf et al., 2016).

Furthermore, although size does matter, any improvement in populations abundance or in exporting individuals decreases very quickly for reserves larger than 1,500 ha (Pérez-Ruzafa et al., 2008). Even, although strongly contested by other authors (Hughes et al., 2016), the usefulness of excessively large reserves has been questioned for improving fishery performance (Fletcher et al., 2015).

At the same time, the effectiveness of a MPA is highly dependent on users' compliance with regulations, and non-compliance is often the rule rather than the exception (Arias and Sutton, 2013; Bergseth et al., 2015, 2017; Arias et al., 2016). This makes proper surveillance and enforcement to prevent or reduce poaching to a minimum are essential in any marine reserve (Davis et al., 2004; McCauley et al., 2016). Enforcement constitutes one of the main costs in the maintenance of an MPA, something that is especially evident in MPAs far from land and in the case of recently proposed and declared mega-parks of more than 250,000 km^2 for which the development and use of relatively expensive next-generation enforcement, such as satellite and drone based patrols will be necessary (McCauley, 2014; Arias et al., 2016; McCauley et al., 2016).

Therefore, it is clear that for any marine conservation plan to be feasible and efficient it is necessary to include the costs derived both from its implementation and maintenance (Mazor et al., 2014a). The socio-economic analyses performed by Alban et al. (2008), which considered all the costs involved in MPA management for the 12 case studies considered by Roncin et al. (2008), showed that, as could be expected, total management costs increase with reserve size, but total cost per ha is minimum for integral marine reserves of between 600 and 1,500 ha (1,400–2,200 m radius).

Taking into account all these ecological, fishing and economic considerations, it may be concluded that the optimum size for marine reserves to improve conservation and fishing yields at minimum cost, would be between 600 and 1,500 ha.

Designing Networks of MPAs

It has been estimated that, to maintain biodiversity, at least a 20–30% of the ocean should be protected (Morgan, 2014; Pressey et al., 2014). At present, only about 3.6% of the ocean has some kind of protection, and just 1.6% is covered by strongly or fully protected (i.e., "no-take" reserves; Lubchenco and Grorud-Colvert, 2015); furthermore, only 2.1% of existing MPAs are actively managed (Sala et al., 2016), i.e., more than 'paper parks'. Increasing coastal area or coastal lengths under protection can be done increasing the size of marine reserves. However, as mentioned above very large marine reserves can be effective for preserving biodiversity and can have higher resilience, but are controversial as a fisheries management tool, while surveillance costs increase exponentially. A good alternative would be to establish MPA networks (Gaines et al., 2010b; Grorud-Colvert et al., 2014; Bode et al., 2016). After the results highlighted above, a network of marine reserves of around 600 ha each separated by tens of kilometres would optimize the balance between conservation efficiency and maintenance costs and have a synergistic effect on the export of biomass in fishing areas between reserves. In addition, the capacity increases and recovery rates of regional, well interconnected stocks after protection is even faster than in individual stocks, with some studies reporting that fish densities recovered in 1.5–2 years after rezoning (Russ et al., 2008).

One important aspect to consider in designing reserve networks is connectivity. Ensuring that reserve populations are connected and maintain genetic fluxes between each other and with non-reserve populations through larval or adult dispersal allows for recovery from disturbance and is a key aspect in resilience (Almany et al., 2009; Calò et al., 2013). However, it is also necessary to optimize trade-offs between connectivity and representation objectives, including species and habitat diversity, while minimizing the risk that multiple reserves will be impacted by catastrophic events (Almany et al., 2009). Spatio-temporal heterogeneity can play an important role in the emergence of homeostatic mechanisms of complex coastal ecosystems (Pérez-Ruzafa et al., 2005) and the introduction of restrictions to connectivity can develop complex structures that enhance biodiversity at genetic and taxonomic levels (Pérez-Ruzafa, 2015).

CONCLUSIONS

In just over a decade, and although many aspects remain to be investigated, much has been accomplished since the first proposals for the creation of marine reserve networks, from the uncertainties that existed (Roberts, 2000; Roberts et al., 2001; Botsford et al., 2003), to our present knowledge of how they function and the effects they have on ecological processes, fisheries and the economic activity.

The appropiate design of MPA networks allows conservation and fishery objectives to be coupled and can provide ecological and recreational services of value (Roberts et al., 2003).

Despite the fact that fisheries in both North East Atlantic and the Mediterranean Sea are governed by the European CFP, great discrepancies in performance have been observed, with recent considerable improvements in stock status in the North East Atlantic being matched by a rapidly deteriorating situation in the Mediterranean region. The control of fishing effort combined with specific technical measures, such as gear regulation, the establishment of a minimum conservation reference size and selective closure of areas and seasons, is the main management strategy adopted by Mediterranean EU countries, while Total Allowable Catches is the major regulatory mechanism in the North East Atlantic (Cardinale and Scarcella, 2017). However, these analyses focus on species fished by trawling generally at greater depths than is usual for MPAs and do not consider local shallow water fisheries, which are the most traditional in the Mediterranean.

By contrast, Mediterranean MPAs work not only by increasing fishing yields, but also by promoting the economy based on recreational diving, tourism, and meeting the objectives of biodiversity conservation, while the Fish Box of northern Europe does not reah spectations.

The holistic ecological considerations discussed above lead us to advocate that an optimal management strategy for designing an MPA (also in the Northern Atlantic) to protect biodiversity and sustain fishing yields consists of combining a network of no-use areas (close to their mature state) with fish boxes (buffer zone maintained by fishing disturbance in a relatively early successional stage, where productivity is higher), under a multi-zoning scheme. In this framework, the importance of no-use areas for fisheries is based on several observations:

- They preserve biological diversity at regional scale, at all levels—specific, habitat/seascape, and also genetic diversity and the structure of populations (Pérez-Ruzafa et al., 2006), allowing natural selection to operate.
- They permit the natural variability of the system to be differentiated from the effects of regulation and to be integrated in appropriate sampling schemes as controls.
- They maintain the natural size and age structure of the populations, hence maximizing potential fecundity, allowing

biomass export to occur from core to regulated areas, dampening the fluctuations derived from deviations from the optimal effort in the fishing zone.

Proper surveillance and enforcement, which prevents or reduces poaching to a minimum, is essential in any marine reserve to ensure its proper functioning and to introduce corrective management measures. At this point, fishermen themselves, as one of the main beneficiaries of the proper functioning of marine reserves, can play an important role in conservation and sustainable practices in a co-managed framework (Claudet and Guidetti, 2010; Hogg et al., 2013).

To evaluate the degree of success of such multi-zone MPAs, we need a suite of fishery and ecological management indicators for both fish boxes and no-use areas. Such indicators must provide a key for convergence of the recovering community in fish boxes to be examined with respect to a mature stage in a given envelope of environmental conditions, using the no-use areas as reference points. Several holistic indicators are usable (Greenstreet and Rogers, 2006; Salas et al., 2006; Shin and Shannon, 2010; Teixeira et al., 2016), including diversity measures, thermodynamically-derived functions (Jørgensen and Mejer, 1979), tropho-dynamic indexes (Tudela et al., 2005), and others more or less specific for exploited marine ecosystems (Shin et al., 2010). Research actions are urgently needed to define those suites of indicators capable of establishing the appropriate reference levels to guide management strategies to recover the increasingly collapsed fish populations in our seas (Rossberg et al., 2017).

We advocate that the optimum size of no-take zones would range between 600 and 1,500 ha, while the size of each zone within the MPA should be scaled to maximize the size of the no-take area to the detriment of buffer zones (about half the size of the no-take area). Any further improvement should come from a network of several MPAs, taking into account that the effects on fisheries improves when the distance between MPAs is no greater than a few tens of kilometres. Such a design fully meets the objective of protecting at least a 20–30% of the coastal area to maintain biodiversity. For pelagic and offshore species, spatial scales should be expanded and larger reserves may be needed, but with the same basic design model. In these cases, surveillance becomes more expensive and new methods, including technological ones, that are effective at the lowest possible cost will have to be developed, also taking into account that international, transboundary collaboration will increase conservation efficiency (Kark et al., 2009; Jay et al., 2016).

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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REVIEW
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Old Info for a New Fisheries Policy: Discard Ratios and Lengths at Discarding in EU Mediterranean Bottom Trawl Fisheries

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Discarding is considered globally among the most important issues for fisheries management. The recent reform of the Common Fisheries Policy establishes a landing obligation for the species which are subject to catch limits and, in the Mediterranean, for species which are subject to Minimum Conservation Reference Size (MCRS) as defined in Annex III to Regulation (EC) No 1967/2006. Additionally, several other initiatives aim to reduce unwanted catches of target and bycatch species, including species of conservation concern. This raises the need to study discarding patterns of (mainly) these species. In this work we collated a considerable amount of historical published information on discard ratios and lengths at discarding for species caught in EU Mediterranean bottom trawl fisheries. The main aim was to summarize the available historical records and make them more accessible for scientific and managerial needs, as well as to try identifying patterns in discarding. We show discard ratios and lengths at which 50% of the individuals were discarded (L_{50}) for 15 species (9 bony fishes, three crustacean decapods, and three elasmobranchs). Discard ratios were usually low for target species such as hake, red mullets and highly commercial shrimps and exemptions from the landing obligation under the *de minimis* rules could be sought in several cases. Discard ratios were usually higher for commercial bycatch species. Discarding is affected by a combination of factors and for a given species, especially for non-target ones, discards are likely to fluctuate within a fishery, across seasons, years, and regions. For most species considered, L_{50}s were lower than the MCRS (when in place) and length at first maturity. L_{50}s of target species, such as hake, were very small due to the existence of market demands for small sized individuals. However, for species of low demand, like horse mackerels, a higher retention size was observed, often exceeding

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MCRS. Lengths at discarding are affected by legal provisions, market demands but also by biological, population, and ecological traits. Understanding the factors that affect discarding constitutes the starting point for designing mitigation measures and management plans to reduce discards and improve the sustainability of the stocks.

Keywords: discarding behavior, multi-species fishery, trawling, unwanted catches, Minimum Conservation Reference Size, landing obligation

INTRODUCTION

Discarding, returning part of the catch back into the sea for whatever reason, is a hot topic for fisheries scientists, managers, and even the wider public (Catchpole and Gray, 2010; Bellido et al., 2011; Condie et al., 2014; Borges, 2015; Sardà et al., 2015; Veiga et al., 2016). The variety of factors (e.g., economic, legal, cultural, natural, biological, technical) affecting discarding render the issue quite complex for fisheries scientists and managers (Bellido et al., 2011; Santiago et al., 2015). Several solutions have been proposed and enforced to mitigate discards (e.g., Sigurðardóttir et al., 2015; Rijnsdorp et al., 2016), however, it is widely recognized that they need to be adapted to the local features of each fishery (Hall and Mainprize, 2005; Johnsen and Eliasen, 2011; Rochet et al., 2014; Sala et al., 2016, 2017).

The recent EU Common Fisheries Policy (CFP) (EU Reg. No 1380/2013), toward a gradual elimination of discards, imposes a landing obligation for the species with catch limits and, in the Mediterranean (where catch limits are applied only for bluefin tuna), for species with defined Minimum Conservation Reference Size (MCRS) [as mentioned in the Annex III of the Council Regulation (EC) No 1967/2006]. The landing obligation raises several issues to stakeholders and presents a wider concern, such as waste management, building port facilities, or adapting the existing ones, handling extra costs related to sorting and on board preservation of the unwanted catch, transportation to land facilities, creation of new markets and the challenge to avoid incentives to fish unwanted catches (Bellido et al., 2011, 2017; Sardà et al., 2015). However, the amounts of unwanted catches that need to be handled are not always well-estimated, especially since the ban applies to a certain number of species. In addition, the regulation states that derogations can be decided and discard plans should be set (Damalas, 2015) on the basis of specific criteria such as the *de minimis* exemption. Further to these timely policy issues, estimates of discards are also important for scientific and managerial goals such as stock assessments, ecosystem modeling, estimation of total catches (including catch reconstructions) as well as for marketing and environmental awareness, e.g., for stock certification (eco-labeling). To tackle the above and to further reduce unwanted catches, understanding of the magnitude of discards and the reasons affecting discarding behavior is essential.

In the past two decades, discards studies in the Mediterranean Sea have increased, while much attention has been placed on bottom trawling, which produces the bulk of discards (Tsagarakis et al., 2014). However, most peer-reviewed studies report discards at the fishery level and the information at the species level is more scattered. This is especially important since target species are not clearly defined in the basin and the fishers actually target a species complex (Stergiou et al., 2003; Caddy, 2009). Species specific discards may vary greatly, from zero (for some highly commercial species in some fisheries) to total discarding (for non-commercial species) (e.g., Carbonell et al., 2003; Damalas and Vassilopoulou, 2013). In addition, commercial bycatch is important in many fisheries and constitute a substantial complementary source of income for the fishers (Tsagarakis et al., 2008). Thus, discard ratios of commercial bycatch may greatly vary seasonally or geographically due to natural conditions, community, state and regulations, and market influence (Eliasen et al., 2014; Tsagarakis et al., 2014). The diversity of the Mediterranean marine environment, the multi-gear, multi-species nature of the fisheries as well as the variant cultural characteristics is expected to differentiate discarding patterns in the basin.

Other than peer-reviewed papers, there is also a great amount of information published in the gray literature which has attracted little attention so far. In the current work we present available published information (i) on species-specific discard ratios as well as (ii) on lengths at discarding for species caught in EU Mediterranean bottom trawl fisheries. The main aim is to summarize the available historical records and make them more accessible for scientific and managerial needs, as well as to try identifying possible patterns in discarding. Special focus is placed on target and main commercial bycatch species as well as on elasmobranchs caught in bottom trawling in the basin.

METHODOLOGY

We collected historical information concerning species-specific bottom trawl fisheries discards in the EU Mediterranean Sea from scientific papers and gray literature, including technical reports. All studies considered collected discards data by using observers on board. The information concerned two aspects. First, we summarized information on discard ratios for species caught in bottom trawl fisheries. Discard ratio was defined as the discarded fraction (in weight) in relation to total catch of a species. In few cases where the discard to marketable ratio (discards/retained catch) was reported, we transformed it to discard ratio (as defined above) for comparative purposes. Along with the discard ratio, additional information regarding the sampling (season, time period), and the fisheries (region, depth stratum, mesh configuration) was noted, where possible. In the Mediterranean Sea, bottom trawl fisheries are officially defined by GSA and by target species (or target assemblages). In addition, in some GSAs, only one bottom trawl fishery is defined. Although—due to data limitations—we did not address specific fisheries, we analyzed the data at the GSA level, which is the best approximation of the fishery that we were able to achieve.

The information derived from 24 sources (six papers in international scientific peer-reviewed journals, three papers in national scientific peer-reviewed journals, three papers in conference proceedings and 12 reports) and concerned 847 records of discard ratios for 71 taxa at the genus or species level in 12 GFCM Geographical Sub-Areas (**Figure 1**) (GSAs 1, 5, 6, 7, 9, 10, 11, 16, 17, 18, 19, 22) during the period 1995–2014. The vast majority of the information came from Spain (663 records) followed by Italy (126 records), Greece (50 records), and Croatia (8 records). Spanish GSA 6 was divided to Northern and Southern parts because the differences in geomorphology and substratum determine the fishing métiers in each zone. Specifically the Southern part (Spanish Levantine coast) is characterized by a large continental shelf of sandy and muddy bottoms, while the Northern area (Catalan coast) includes more abrupt geomorphological structures like canyons and narrow continental shelf. Furthermore, in some studies (STECF, 2006, 2007; Bellido et al., 2014) discard ratios were reported for the entire Spanish Mediterranean and not per GSA. Discard ratios were more frequently reported for bony fish; for crustaceans they were mainly reported for the most important commercial species while the information was scarce for other invertebrates. Several elasmobranch species were covered, obviously because they are of interest for conservation; however, very few records per species were usually available.

For the species with the largest amount of records we present box-plots of all the records of discard ratios in the EU Mediterranean. In addition, we present this information at the GSA level aiming to identify patterns and factors affecting discards. It should be noted here that the different horse mackerel species (*Trachurus* spp.) were pooled together for the purpose of this presentation since (i) they are often reported at the genus level, (ii) their identification at the species level may be spurious and (iii) they are often marketed together.

We did not try to estimate mean values of ratios because (i) of the variability of the data (different gears, time periods, and sampling designs) and (ii) in order to do this correctly discard ratios should be weighted with landings of the species in each record (an information which was not available). Furthermore, we did not explore the interranual progress of discard ratios since the level of aggregation of the discard ratios reported in the original sources differed; some papers/reports reported values averaged over several years, while others mentioned values for a single sampling season.

Second, we collected information on lengths at discarding. These studies are scarcer and may report different kinds of information, i.e., length range or L_{50} (the length at which 50% of the individuals are discarded after sorting on board). Thus, we focused only on L_{50}s of species discarded and, again, additional information on the sampling and the fisheries was collected. In total, we collected 174 records of L_{50} for 30 species in 8 GSAs, derived from five studies (four papers in international or national scientific peer-reviewed journals and one report). Only records from Spain (18 records), Italy (54 records), and Greece (102 records) were available.

For selected species we graphically represent box-plots of L_{50}s in comparison with MCRS (where applicable) and Length at First Maturity (LFM). The graphical representations enable to instantaneously evaluate if fishermen were discarding mature or immature individuals as well as below or above MCRS. Despite that some differences in LFM may have been reported across the basin for a given species, we assumed the same LFM value for each species independent of the GSA. Specifically the median LFM for each species was calculated based on the data reported in Tsikliras and Stergiou (2014) (**Table 1**). For crustacean species not reported in Tsikliras and Stergiou (2014) LFM was calculated by reviewing other available scientific literature (Supplementary

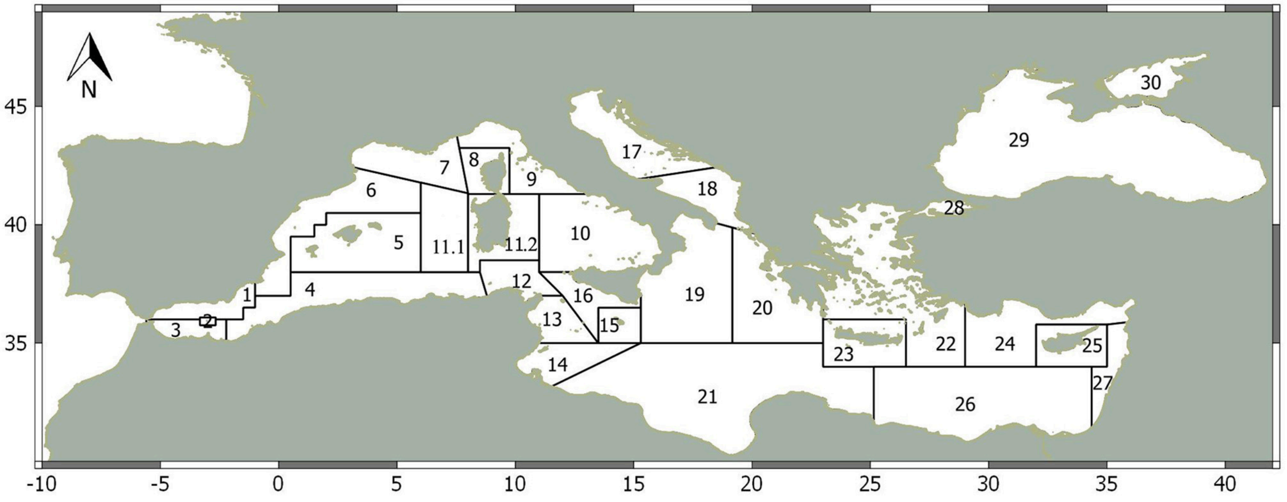

FIGURE 1 | Geographical Sub-Areas (GSA) according to GFCM division.

TABLE 1 | List of species and their code names presented in the Figures.

Scientific name	Common name	Code	LFM (mm)
BONY FISHES			
Boops boops	Bogue	BOG	139.5
Lepidorhombus boscii	Four-spot megrim	LDB	138
Merluccius merluccius[a]	Hake	HKE	305
Micromessistius poutassou	Blue whiting	WHB	210
Mullus barbatus[a]	Red mullet	MUT	129
Mullus surmuletus[a]	Striped red mullet	MUR	155
Pagelllus erythrinus[a]	Red pandora	PAC	164
Phycis blennoides	Greater forkbeard	GFB	200
Trachurus sp.[a]	Horse mackerels	JAX	191
ELASMOBRANCHS			
Etmopterus spinax[b]	Velvet belly lanternshark	ETX	–
Galeus melastomus	Blackmouth catshark	SHO	489
Scyliorhinus canicula	Lesser spotted dogfish	SYC	420
DECAPODS			
Aristeus antenattus	Red shrimp	ARA	27.8
Nephrops norvegicus[a,b]	Norway lobster	NEP	–
Parapenaeus longirostris[a]	Deep water pink shrimp	DPS	24.3

The Lengths at First Maturity (LFM) in mm (from Tsikliras and Stergiou, 2014 and references listed in Table S1 of the Supplementary Materials) are indicated. Lengths are Total Length for fish and Carapace Length for decapod ctustaceans.

[a]Species with MCRS; [b]Species with no information on L_{50}.

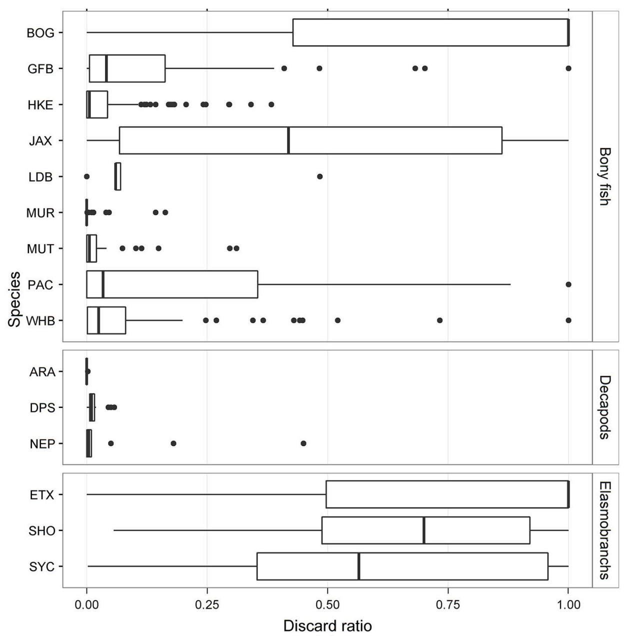

FIGURE 2 | Box-plots of discard ratios (discards/total species catch) in EU Mediterranean bottom trawl fisheries for selected bony fish, elasmobranch, and decapod species. See **Table 1** for species codes.

Materials, Table S1). The median values were used instead of mean, because they are not influenced by the outliers in the dataset (Zar, 1996). If LFM differed between genders, the more conservative (larger) median value was used.

For the sake of simplicity, in the presentation of the results we show (a) the most commercial species, (b) some common bycatch species with commercial interest, and (c) some common elasmobranch species in the bottom trawl fisheries. Nevertheless, full records that we collected are listed in the Supplementary Materials accompanying this paper.

RESULTS

Discards Ratios

All species specific discard ratios that derived from the literature review as concerns the EU Mediterranean bottom trawl fisheries are listed in Table S2 of the Supplementary Materials. **Figure 2** summarizes the compiled published information on discard ratios for the most frequent species found in our database, for the whole Mediterranean. These include nine bony fish, three elasmobranch, and three decapod species. Both target species, such as *Merluccius merluccius* (hake), *Mullus barbatus* (red mullet), *Aristeus antennatus* (red shrimp), and some abundant commercial bycatch species such as *Boops boops* (bogue), *Trachurus* sp. (horse mackerels), *Phycis blennoides* (greater forkbeard), and *Micromessistius poutassou* (blue whiting) were included in this analysis (**Figure 2**, **Table 1**). The box-plots highlight the highly fluctuating discard ratios as a characteristic of these fisheries; great range in discarding was observed among and within species, in different areas from the western to the eastern Mediterranean as well as for target and commercial bycatch species (**Figure 2**). Part of this variation is also due to the disaggregation of discard ratios by season, year, location, gear characteristics, depth stratum, and/or other (Supplementary Materials, Table S2), as each record in the data set was treated as a different entry in the data analysis. In addition, the large number of outliers (**Figure 2**) is probably in close relation to the latter, as some outliers of high discard ratio can be attributed to low captures or small sizes of a species in a given season, depth stratum, etc.

Discard ratios for target species such as hake, red mullet, stripped red mullet, red shrimp, *Nephrops norvegicus* (Norway lobster), and *Parapenaeus longirostris* (deep water pink shrimp) are very low (<10% and often <2% of the total species catch; **Figure 2**, Supplementary Materials, Table S2). In contrast, discarding for bogue and horse mackerels exceeded 40% in the majority of records (**Figure 2** and Supplementary Materials, Table S2). Discard ratios were also very high (usually >65%) for the elasmobranchs considered.

The above information is also analyzed by country and GSA in **Figure 3** (bony fish) and **Figure 4** (decapods and elasmobranchs). High variability in discarding is observed among countries and GSAs. Even though discard ratios for some species were similar and almost always negligible across the basin, regional variations were observed for others (**Figures 3**, **4**). Hake, the main target species for the shelf and shelf-break demersal fisheries, showed low discard ratios (usually 0–5%) for almost all areas studied, with some exceptions in certain

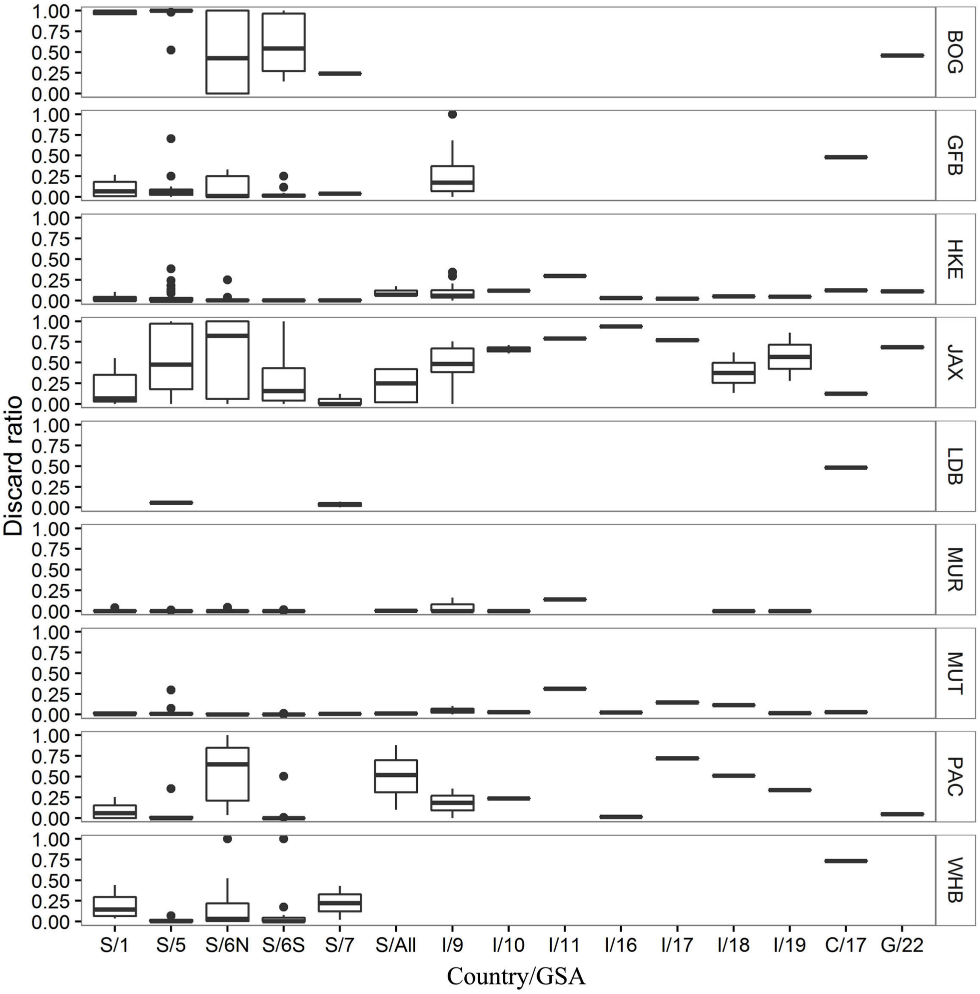

FIGURE 3 | Box-plots of discard ratios for main target and commercial bycatch bony fish species, per country/GSA. C, Croatia; G, Greece; I, Italy; S, Spain. See **Table 1** for species codes.

areas (e.g., GSAs 5, 9, and 11) where few records of higher discards that exceeded 20% were observed (**Figure 3**). Red mullet and stripped red mullet can be considered as species with negligible discards throughout the basin (**Figure 3**) except GSA 11 where the discarded fractions exceeded 10%. Bogue, a coastal species, is a special case in the Mediterranean, since it was almost completely discarded in the west (Spain) but showed commercial importance in the east (Greece). The other coastal species, *Pagellus erythrinus* (red pandora), also showed different discard ratios depending on the areas, i.e., lower discard ratios in most Spanish GSAs, Italy and Greece compared to Spanish GSA 6N, the entire Spanish Mediterranean and Italian GSAs 17, 18, and 19 (**Figure 3**). Horse mackerels were probably the species with the higher fluctuations; they seemed to have lower discards in Croatia (GSA 17), and some Spanish GSAs (GSAs 1, 5, 6S, 7) compared to Greece (GSA 22), most Italian GSAs and Spanish GSA 6N. The discard ratios of greater forkbeard, blue whiting, and *Lepidorhombus boscii* (four-spot megrim) were quite homogeneous in the western and eastern areas with the exception of Croatia where the ratios were generally higher (**Figure 3**).

For crustaceans, the main targets of the shelf-break to middle slope trawl fisheries, discards were almost null for red shrimp and deep water pink shrimp in the Western and Eastern areas respectively, and very low for Norway lobster in almost all areas (**Figure 4**). As for the three most common elasmobranchs presented, *Galeus melastomus* (blackmouth catshark), *Scyliorhinus canicula* (lesser spotted dogfish), and *Etmopterus spinax* (velvet belly lanternshark) a wide range in discard ratio was observed but they were usually discarded by 40–100% (**Figure 4**).

Seasonal discard ratios were mainly available for Spanish GSAs and Italian GSA 9 and are illustrated only for bony fishes in Figure S1 of the Supplementary Materials. However, taking into account the data available, no clear seasonal patterns were observed.

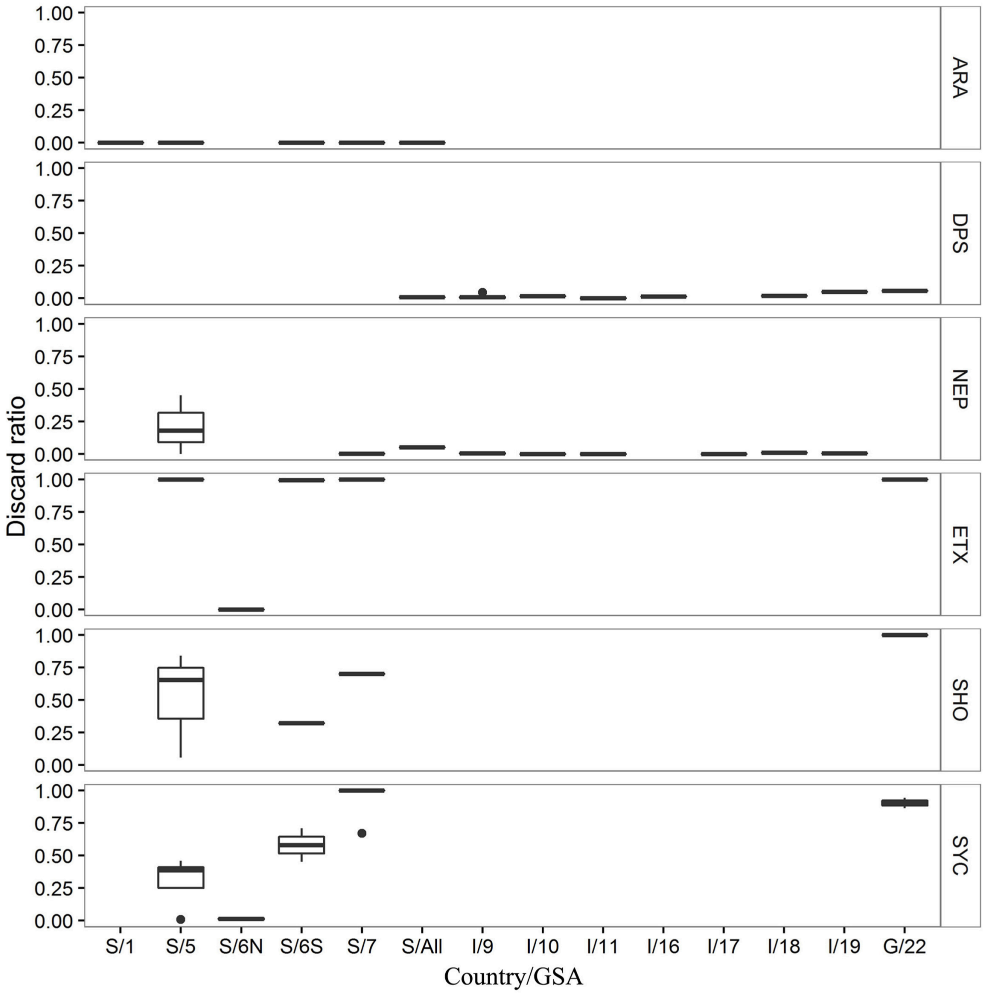

FIGURE 4 | Box-plots of discard ratios for main decapod (ARA, DPS, NEP) and elasmobranch (ETX, SHO, SYC) species per country/GSA. G, Greece; I, Italy; S, Spain. See **Table 1** for species codes.

Lengths at Discarding

The data from the literature review on L_{50}s are listed in Table S3 of the Supplementary Materials. **Figure 5** summarizes the L_{50}s for each country and GSA for the same species presented earlier, with the exception of Norway lobster and velvet belly lantern shark for which no records of lengths at discarding were retrieved. Together with the L_{50} values, the MCRS (where applicable) and LFM are plotted (**Figure 5**), which helps to evaluate if fishermen in a certain country were discarding mature or immature individuals, below or above MCRS. Within species geographical differences in the lengths of discards were observed; however they were usually not as pronounced as the differences in discard ratios. All species were retained at sizes below the LFM with the exception of four-spot megrim in Greece and Italy, greater forkbeard in GSA 22, horse mackerels in GSAs 19 and 22 as well as blue whiting in GSA 19 (**Figure 5**). All species with MCRS defined in Council Regulation (EC) No 1967/2006 were also retained at sizes smaller than the legal, with the exception of horse mackerels (**Figure 5**). Hake L_{50} was closer to MCRS in GSAs 22 and 19 than in other areas, while red pandora in Italian GSA 19 and red mullet in Greek GSA 20 were retained very close to MCRS. In addition, differences were observed also within the same country; for example in Spain, hake L_{50} was larger in GSAs 1 and 5 compared to GSA 6N (**Figure 5**). Another interesting outcome of the graphs is that the retention sizes of the target species were very small compared to bycatch species even if they concerned larger species (with larger maximum length). For example, the median L_{50} for hake is 10–17 cm (depending on the country) and the median L_{50} for horse mackerels is 18–21 cm (**Figure 5**, Supplementary Materials Table S3), despite that hake and horse mackerels LFM (Lmax) are 30.5 (140) and 19.1 (70) cm respectively (**Table 1**; Froese and Pauly, 2016).

DISCUSSION

Bottom trawling produces the bulk of discards in the Mediterranean fisheries (Tsagarakis et al., 2014). Thus, it is not surprising that there is a large amount of information

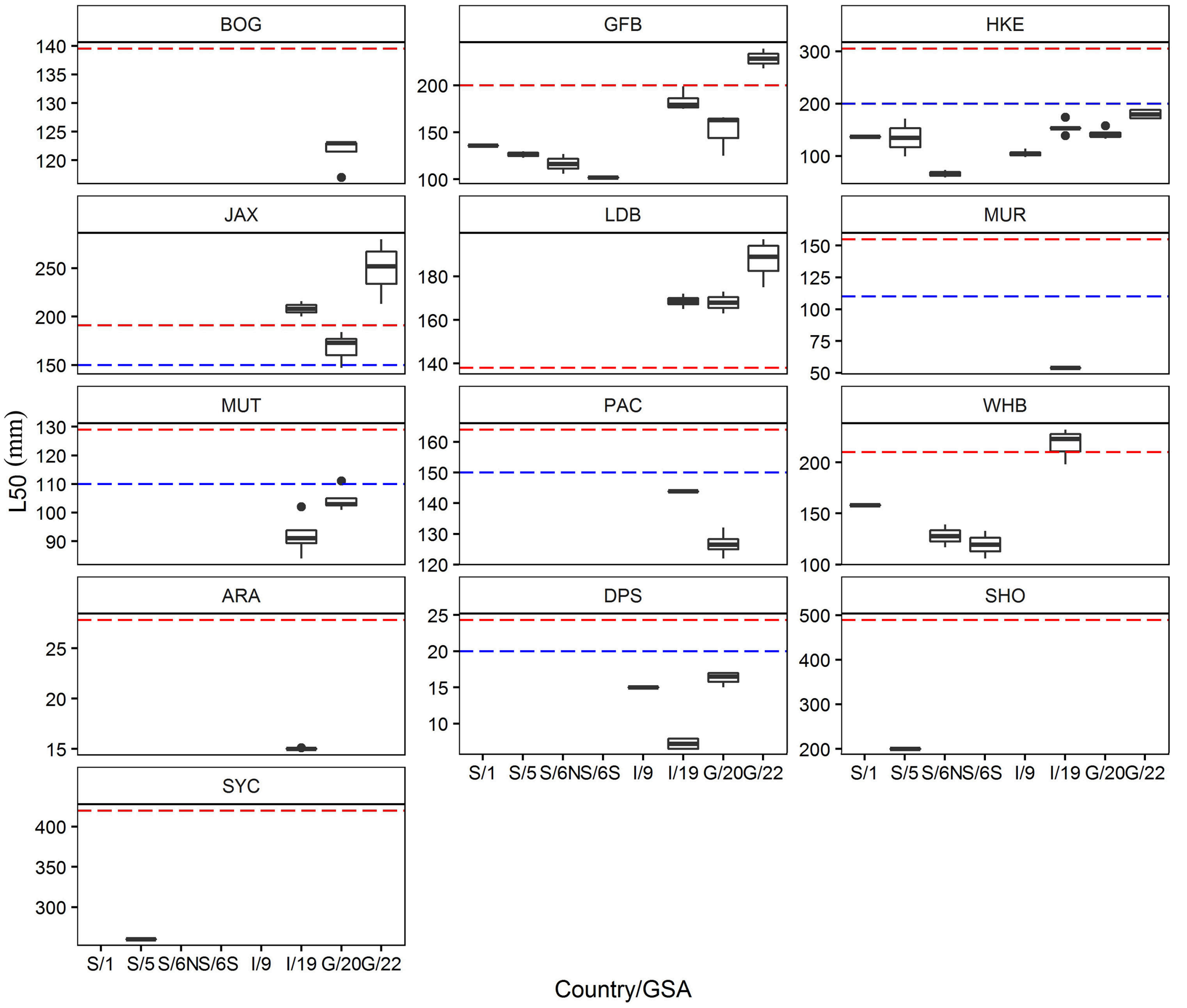

FIGURE 5 | Box-plots of L_{50} (lengths at which 50% of individuals are discarded; in mm) for main bony fish, elasmobranch, and decapod species caught in bottom trawls per country/GSA (G, Greece; I, Italy; S, Spain). MCRS (blue horizontal lines) and lengths at first maturity (red horizontal lines) are also indicated. Lengths for crustaceans (DPS, ARA) refer to carapace length while for fish to total length. See **Table 1** for species codes.

across the basin as concerns discards of the bottom trawl fisheries. Because of the nature of discard research, there are many interesting discard studies as gray literature (reports, working documents, national reports to authorities, etc.), which remain quite often unavailable to the scientific community. This paper makes available some of this information in a synthetic approach, which is quite important for future research and management, e.g., for use in stock assessment and ecosystem models, for the characterization of specific bottom trawl fisheries and for decision making including the implementation of the CFP. As expected, the information was more frequent for the commercially most valuable and most abundant species in the bottom trawl fisheries, thus, inevitably, we chose to focus our presentation on these. Discards studies in general consider and focus their estimations on valuable commercial species; however, the multi-species nature of catches in the Mediterranean, driven by the diversity of assemblages and bottom substrata (de Juan et al., 2013), sets necessary to include additional species in the future studies. This is important for the sustainable exploitation of the resources in the context of the Ecosystem Approach to Fisheries, including Integrated Ecosystem Assessments (e.g., ICES, 2016), and for the goal to reduce the quantities of unwanted catches.

The information that we managed to retrieve was not equally distributed among EU countries, with Spain having more detailed information at temporal and spatial scale, followed by Italy and Greece, while only few records were available for Croatia and none for other EU countries. Most of the information derived from research and monitoring projects related to discards in the period 1995–2000 (e.g., West Mediterranean: Carbonell et al., 1997; Central and East Mediterranean: Tsimenides et al., 1997), thus this period is highly represented in the database that we built following the literature review (Supplementary material, Tables S2, S3). It seems that the first monitoring projects quantified discards in much detail and described an issue which had attracted little attention up to then. In the following period the interest in publishing on this field faded and/or the next projects and analyses focused less on the description of the issue itself and more on the factors affecting discards. Undoubtedly, more historical data on discards exist in databases and technical reports that are not publicly available and were not accessible to us. The inclusion of this information could complete the gaps in order to shed light on the evolution of trawl discards in the Mediterranean in terms of discard ratios, diversity and size structure of discards. These questions are important not only for the design and application of the CFP but also for the Marine Strategy Framework Directive (EU Directive 2008/56/EC), for the Ecosystem Approach to Fisheries and for the evaluation of policies such as technical measures (e.g., mesh configuration) and spatial restrictions included in the Mediterranean Regulation [Council Regulation (EC) No 1967/2006]. However, given that the general patterns reported in the literature, highlighted in our analysis and discussed below (i.e., low discarding of valuable species and large fluctuations of commercial bycatch) are common across the basin, the inclusion of additional data is not expected to significantly alter the picture presented here. In any case, improving access to such data would favor fisheries research needs and management in the Mediterranean. Furthermore, the use of raw data collected under the EU Data Collection Framework could help tracking the progress of the discards issue from the onset of the first monitoring programs until present, across the basin.

Our review showed that discard ratios highly fluctuated within and among species. Several characteristics of the fisheries in the Mediterranean Sea affect discarding patterns: (i) trawl fishing is essentially multispecies and targets a species complex rather than one or two species (Caddy, 2009), (ii) there is a great diversity of species in the catch including, aside from the so-called "target" high-commercial species, the fraction of bycatch that consists of species which are not marketable and of species which may constitute an important commercial fraction and are partly retained, and (iii) there are no overquota discards and MCRS seems the only management measure directly affecting discarding behavior. As a result of the above, the discarded fractions of the so considered target species were usually very low or even negligible and comprised damaged or undersized specimens (Carbonell et al., 2003; D'Onghia et al., 2003; Sartor et al., 2003; STECF, 2006). This was obvious across the basin for all the main commercial species (hake, red mullet, stripped red mullet, Norway lobster, deep sea pink shrimp, red shrimp) of the bottom trawl fisheries considered in our analysis. Only few exceptions were evident in which high discard percentages generally coincided with zones in which MCRS are more respected; this was, for example, the case for the Balearic Islands (GSA5) where some outliers of high discard ratios of hake and a discards percentage of Norway lobster higher than in other Mediterranean regions (around 20%) were observed. In this area discards seem to be more associated with undersized discards and local compliance with MCRS regulations. In contrast, in other areas (such as GSA 9 and 11 for hake and GSA 11 for red mullets) the high discard ratios reflected the concentration of the fishery on nursery areas and in the recruitment periods. Especially in GSA 11 the large discard ratios of hake, red mullet and stripped red mullet are partly attributed (i) to the extended presence of nurseries of these species (Colloca et al., 2015) which leads to relatively large catches of juvenile fish that are discarded, as well as (ii) to the targets of the bottom trawl fishery in Sardinia. Specifically, the majority of vessels off Sardinia exploit the deep part of the continental shelf (nursery of hake) as well as the slope, where the main targets are deep water pink shrimp, Norway lobster, red shrimp and giant red shrimp, *Aristeomporpha foliacea* (Follesa et al., 2012); therefore, species like hake and red mullets are considered as by catch and only the bigger specimens are retained. However, due to the inclusion in the analyses of discard ratios estimated only based on weight of catches, the ratios may not always reflect high discarding of juveniles in nursery areas (e.g., for hake in Gulf of Lions—GSA7). Apart from these scarce exceptions, low ratios were the rule for target species across the basin, which additionally seemed to be sustained throughout the years. Therefore, exemptions from the landing obligation according to the *de minimis* rule (Article 15 of the EU Regulation 1380/2013) may be sought for several species in various trawl fisheries in the frame of discard plans, in line with the reformed CFP.

However, most studies in the Mediterranean report relatively low proportion of key commercial (i.e., target) species in the catch, even in cases that target species are clearly defined (e.g., Carbonell et al., 2003; Atar and Malal, 2010). Nevertheless, it is reported that a great amount of the bycatch is commercialized since numerous bycatch species are occasionally landed, reducing the discarded quantities to lower levels. For example, in the strait of Sicily, for 1 kg of targeted shrimps 9.6 kg of bycatch was produced but 4.4 kg of this was commercialized (Castriota et al., 2001) with an estimated crustacean (*P. longirostris*, *N. norvegicus* and *A. foliacea*) discard rate of 21.7% in spring 2001 (Vitale et al., 2006). Despite the commercialization of several non-target species, a large number of species that are always totally discarded are included in the catch (e.g., Machias et al., 2001: 142 species in the Aegean and Ionian; Sánchez et al., 2007: 49 species in the Adriatic, 35 species in the Catalan; Tsagarakis et al., 2008: 47 fish species in the Ionian; Bellido et al., 2014: Up to 60% of species in Mediterranean bottom trawl fisheries).

The species belonging to the commercial bycatch were usually characterized by higher discard ratios than the most valuable species and exhibited higher fluctuations geographically (e.g., Machias et al., 2001) and seasonally (Tsagarakis et al., 2008; Pennino et al., 2014), ranging from zero to almost full discarding in some sampling periods. The range of the fluctuations also depended on the species, since a species which is marketed in one country (or even GSA) may not be marketed in the others. Horse mackerels exhibited great differences in discarding within and among GSAs since they were subject to high grading regardless their sizes in Greece and most Spanish and Italian GSAs, but the discard ratios were lower in Croatia, and Spanish GSAs 1, 6S, and 7. On the other hand, bogue, a coastal species, was more appreciated in Greece than in Spain as demonstrated by the lower discard ratio in the former; commercialization in the eastern Mediterranean is mainly oriented to human consumption while in the western part it is related with use in aquaculture. Regional differences in the discard ratios of red pandora, which is also a coastal species, can be due to different market preferences for this species or for specific sizes. Greater forkbeard is mainly a bycatch of the deep demersal fishery, usually caught in small to intermediate biomasses and abundances and quite homogeneous discard ratios were observed in the western and eastern areas. Regarding blue whiting, an important bycatch species without MCRS at EU level and for which discarding is due to market preferences, a quite homogeneous percentage of discards was noted, at least for the western GSAs where most of the information derived from. The three species of sharks, which are the most studied in the discards literature and the most abundant in demersal fisheries, represented a different percentage of discards, always related with small sizes. Specifically, in the Balearics (Spain), 60% by weight of the lesser spotted dogfish and 35% of the blackmouth catshark were landed (Carbonell et al., 2003) while much less was commercialized in the central Aegean (Greece) (Damalas and Vassilopoulou, 2011). The velvet belly lanternshark was almost always discarded across the basin but is now partially commercialized, at least in the Balearic area (A. Carbonell, unpublished data).

Regional and seasonal environmental differences (e.g., depth, substrate types, productivity), as well as ecological and biological factors crucially affect catch and discards (Carbonell et al., 2003; Damalas and Vassilopoulou, 2011; Carbonell and Mallol, 2012). The synergistic effect of such factors determines (among others) the size distribution (e.g., mean length) of the populations which, in turn, is largely responsible for regional and/or bathymetric differences in discard ratios. As a result, nursery grounds are often characterized by high discard ratios (e.g., Paradinas et al., 2015). Further to the above, legal measures (e.g., area closures), fishers' behavior, gear characteristics as well as overexploitation leading to decreased abundance may further affect the bycatch and discarding of species (Aldebert, 1997; Damalas and Vassilopoulou, 2011; Eigaard et al., 2016, 2017). Nevertheless, discarding in the Mediterranean is mainly market driven and is further affected by socio-cultural traits which eventually affect market demands (Tsagarakis et al., 2014). At the haul level, discards of bycatch species may be high when their catch is too low to be sold or when the catches of the target species are adequate enough to provide a high income to the fisher (Tsagarakis et al., 2008). At the end, the decision to discard or not is affected by a combination of factors which is not always easy to disentangle. For example, in Spanish GSAs, large differences in within-species ranges of discards were observed (e.g., for horse mackerel and blue whiting) which could be mainly attributed either to natural conditions and population structure in different regions, or to differences in sociocultural characteristics and gastronomic habits along the Spanish Mediterranean coast.

Further to the above, although no consistent seasonal patterns were identified, discard ratios of several species were found to differ with season. This could be due to seasonal recruitment and/or migrations of species to more coastal zones for spawning or recruitment, during which increased trawl catches are observed leading to higher discards. Carbonell and Mallol (2012) found seasonal influence on discard rates, but different seasons had higher discards depending on the areas, i.e., spring-summer in the Gulf of Lions and winter in the Balearic Sea. In their study, the highest discard rates in the Gulf of Lions continental shelf were linked to pulses of productivity, during which recruitment of some target species, like hake, takes place in the area, and at the same time planktivorous species, like sardine, concentrate on the shelf for spawning and are massively caught in the trawl fishery (Carbonell and Mallol, 2012). These planktivorous fish are largely discarded due to a French regulation that only allows to retain 10% of the trawl catches of pelagic species. In the case of the Balearic area, the increased discarding in winter was also related with pulses of higher productivity in this zone, after the exhaustion of resources and food in summer (Carbonell and Mallol, 2012).

Fishers' behavior may also influence seasonal discarding either by changing fishing locations in order to target different assemblages (Carbonell and Mallol, 2012) or by changing their discarding behavior. Tsagarakis et al. (2008) also described a transfer of species from the discarded to the marketable fraction toward the end of the fishing period in the Ionian Sea, which was attributed to the reduction of target species in the catch which stimulated a change in fishers' discarding behavior toward increased commercialization of bycatch. In addition, as in the case of the velvet belly lanternshark in the Balearics mentioned above, there may be a tendency for a reduction of discards of some species through time (from the first studies to now). Whether this tendency is true remains to be further explored, however it is expected to occur due to (i) the familiarization of the consumer with certain species, (ii) the overexploitation in the Mediterranean fisheries that sets some target species less abundant and which forces to introduce additional species in the commercial fraction, (iii) the increased abundance of invasive species (e.g., Edelist et al., 2011) and, of course, (iv) the fishers' need to sustain or even increase their revenues. These reasons show that discarding could be more considered a behavioral issue of the fishery than a biologically induced cause.

A recent study reports that the level of discarding of MCRS-regulated species in Mediterranean bottom trawl fisheries is lower in relation to other EU regions, and landing rates largely exceeded those of discards, with some exceptions (Uhlmann et al., 2014). This can be partly attributed to the smaller MCRS applied in the Mediterranean, a lack of MCRS-compliance (Damalas and Vassilopoulou, 2013), and the absence of over-quota discards in the quota-independent management system of Mediterranean demersal trawl fisheries (Catchpole et al., 2014). On the other hand, criteria to make use of some fish products and reject some others should be found in the cultural and social heritage in different areas, which finally result in the existence or absence of a market for those products. Unfortunately, there is still a black market of specimens under the legal MCRS in some

Mediterranean areas where there is a tradition of consuming them although awareness against the consumption of juveniles is progressively increasing (Bellido et al., 2017).

Indeed, our findings showed that the lengths at discarding in the Mediterranean bottom trawl fisheries were generally small and only in few—usually bycatch—species L_{50} exceeded 20 cm. Tsagarakis et al. (2008) estimated the fish community-wide (independent of species and seasons) L_{50} to 13.6 cm in the Ionian Sea trawl fishery. This is due to the predominance of small sized species in the Mediterranean fished community (Edelist et al., 2014), to the massive catches of juveniles of certain species throughout the years (Farrugio et al., 1991), to the existence of market demands for small individuals as well as to the continuous overexploitation of resources that leads to a predominance of small sized populations. In addition, trawl selectivity in the multi-species Mediterranean fisheries does not always succeed to substantially reduce catches of juveniles of most species without reducing the targeted catch of other species (Sala et al., 2015).

Within species, variations were also observed as concerns the sizes at discarding. The sizes at discarding are influenced by a combination of factors such as MCRS, gear selectivity, catch composition, market demands and recruitment period, while even weather conditions may affect sorting by the crew (Machias et al., 2004; Damalas and Vassilopoulou, 2013; Sartor et al., 2016). Environmental parameters such as substrate type, depth and season have been shown to widely affect population structure and species composition, which largely determine what is discarded. Nursery grounds of several species in the Mediterranean Sea are located in the continental shelf and/or on the shelf-break (e.g., Carbonell and Mallol, 2012; Colloca et al., 2015; Paradinas et al., 2015) and can therefore be associated with small retention sizes, at least in certain seasons.

Above all, the effect of market drivers is crucial in determining discarding practices, especially since fishers' responses to market demands may be more important than legal provisions particularly in the Mediterranean, where EU countries appear to invest little in regulation enforcement as compared to other EU regions (Wallis and Flaaten, 2000). This cannot be contested given that L_{50} of most regulated species were found to be smaller than MCRS. Given the existence of black market for undersized individuals, it is doubtful whether the landing obligation in the Mediterranean quota-free management system is meaningful; in contrast, it is possible to lead to even higher (illegal) commercialization of undersized catches since they will be then legally brought to land (Bellido et al., 2017). The importance of market drivers is also reflected in the between-species differences in sizes of discards, with species of higher commercial value having lower retention sizes than species of lower commercial value, despite the fact that they may have larger MCRS and maximum length. This was clear in the retention sizes of e.g., hake and red shrimp which were often similar to or smaller than those of horse mackerels and deep water pink shrimp respectively, despite the fact that the latter ones are species with generally smaller specimens, smaller maximum size, LFM, and MCRS. Obviously, as already highlighted in other studies, discards of species with low commercial value include both undersized individuals and specimens larger than the MCRS (if applicable) (Sartor et al., 2016).

The L_{50}s were also much smaller than LFM, showing that juvenile fish are caught and marketed in the bottom trawl fishery, legally or illegally, depending on whether individuals are larger or smaller than the MCRS respectively. The discrepancy between retention sizes and LFM is expected to impede the sustainability of the stocks (Colloca et al., 2013). On the other hand, the probable revision of MCRS (in order to approximate LFM) seems unrealistic (at least for some species) and unlikely to deliver the desired results. Specifically, it is doubtful if it would drive fishers to avoid catches of juveniles and it would possibly lead to a further bloom of the black market for undersized individuals (Bellido et al., 2017). In any case, it is widely accepted that alternatives to the current management tools are needed in the Mediterranean regarding technical (e.g., Sala et al., 2015) as well as other policy measures (e.g., Bellido et al., 2015; Damalas, 2015).

According to (Sala et al., 2013) there are three main bottom trawl typologies in the Mediterranean: (i) two-panel trawls which have low vertical opening (1–2 m) and are usually used to target mixed demersal species, (ii) four-panel trawls with increased vertical opening (2–4 m) which are generally used to target crustaceans, and (iii) the least common beam trawls which are generally used in shallow waters for specific targets. Alongside the coast of the Mediterranean EU countries there are many sub groups of these trawl typologies but since the enforcement of Council Regulation (EC) No 1967/2006 all of them have either 40 mm square mesh codend or 50 mm diamond mesh codends. The only exception is Croatia which adopted these measures after joining the EU in 2013. This is important to emphasize because underwater observations showed that the majority of fish escape through the codend meshes during the tow (Wileman et al., 1996). Since the gear size selection with the above mentioned codends is relatively poor (Sala et al., 2015), and was even lower in the past, the variation in L_{50} values reported in this paper depend solely on the fishermen selection.

Trawling gears could be made more selective by using larger mesh sizes or incorporating special excluding devices, such as those based on rigid grids or juvenile excluder devices. Notwithstanding, these solutions may be challenging to apply in Mediterranean for social reasons, but their compulsory use for increasing selectivity deserve attention. The history of technical measures applying in European fisheries legislation within the framework of the Common Fisheries Policy (CFP) is one of numerous regulations, amendments, implementing rules and temporary technical measures introduced as stop-gaps to resolve emerging problems. The regulatory structure for technical measures has become highly complex and somewhat disjointed. A recent EU proposal [COM (2016)134] defines baseline technical measures to establish core selectivity standards for each regional sea basin. These baseline measures set minimum mesh sizes for towed and static nets, closed areas and minimum conservation sizes. The proposal envisages that regional groups of Member States would be able to introduce alternative technical measures to these baselines on the basis that it can be demonstrated that these measures deliver similar conservation benefits in terms of exploitation patterns and level of protection for sensitive species and habitats to those they are intended to replace. The repeated failures to reach agreement on a new technical measures regulation clearly highlight the need for a new approach. This should be based on: Simplification, adaptation of decision-making to the Lisbon Treaty, strengthening the long-term approach to conservation and resource management including tackling the discards problem, regionalization, further stakeholder involvement and more industry responsibility (i.e., a culture of compliance).

The current review concerns studies that took place before the recent reform of the CFP and of course before the onset of the landing obligation, which is designed to be gradually implemented starting from 2017 in Mediterranean bottom trawl fisheries. As a consequence, with some exceptions (e.g., Damalas and Vassilopoulou, 2013; Sartor et al., 2016), the studies were not designed to meet the needs of the CFP as concerns discards, i.e., to quantify the unwanted catches of regulated species (subject to MCRS). In the spirit of the CFP, unwanted catches include both discards and undersized individuals that may be (illegally) marketed. Therefore, the two terms (unwanted catches and discards) are not identical and the results of historical studies cannot be directly applied to justify that a *de minimis* exemption should be granted. Nevertheless, the fact that the L_{50}s of most regulated species were found below MCRS does not provide information on the contribution of the undersized fraction to landings, which may be relatively low. Thus, future studies on discards should also include the estimation of unwanted catches as priority in order to meet management and policy needs.

AUTHOR CONTRIBUTIONS

VV, KT, JB, AC, AS, JMB, AE, and AM designed the study. KT, AC, and JB analyzed the data and wrote the first draft. All authors performed a literature review and/or contributed with data, interpreted the results and critically revised and approved the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fmars.2017.00099/full#supplementary-material

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Preference Modeling to Support Stakeholder Outreach toward the Common Fishery Policy Objectives in the North Mediterranean Sea

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Participatory management is a working method of paramount importance based on the principles of knowledge sharing and accountability for addressing the sustainable management of the fishery sector. To approach this multidimensional problem we applied two Multi Criteria Decision Analysis (MCDA) methods, the Analytic Hierarchy Process (AHP), and the Non-Structural Fuzzy Decision Support System (NSFDSS), which were applied incorporating uncertainty to generate probabilistic rankings. The NSFDSS technique was applied for the first time to address a fishery problem. Two surveys were carried out among Mediterranean Advisory Council (MEDAC) stakeholders with different backgrounds. By the two surveys we: (i) made an AHP test for exploring stakeholders' perception of the objectives and indicators used in the monitoring of the stocks, ecosystem, and fisheries, and (ii) introduced the NSFDSS technique, gathering feedback on stakeholders' preferences on management options for improving fishery sustainability (e.g., reducing discards, improving ecosystem state, and economic yield in the long term). In the AHP the respondents were asked to evaluate the importance of one objective against another according to a scale of semantic scores from 1 to 5, whereas a simpler scoring scale, with only three possible options, was used in the NSFDSS. The two MCDA methods were proven to be useful to elicit stakeholders' view on the potential effects of key issues on economic and environmental fishery sustainability. The results showed stakeholders' awareness of the fact that the reproductive potential should be secured by checking mortality and/or fishing intensity. Consistently, among the ecological indicators that are tracking the fisheries policy objectives, a higher rank was attributed to "*mean size of the spawners*," while cost efficiency was considered to be essential for improving profits. Regarding the economic indicators, stakeholders gave higher priority to "*revenue*" in comparison to "*production (catches)*," which is a sign of awareness that increasing fish production does not necessarily turn into increased revenue. Among the different management strategies, "*fleet withdrawal*" (scraping) was considered as the worst option, while the "*combination of measures*" was considered to be the best alternative for achieving a sustainable fishery in the long term.

Keywords: multi criteria decision analysis, data collection framework, indicators, fishery management plan, north Mediterranean Sea

INTRODUCTION

Participatory management is widely recognized as a working method of paramount importance, based on the principles of knowledge sharing, accountability, and legitimacy, for addressing the sustainable development of the fishery sector. Industry–science cooperation could ensure more coherent information, enhance credibility, as well as contribute to the progressive implementation of an Ecosystem Approach to Fishery Management (EAFM). This process entails the integration of stakeholder's local and traditional knowledge on both research-based advice and identification of management directions (e.g., Garcia and Cochrane, 2005; Cochrane et al., 2007; Rochet et al., 2008; Röckmann et al., 2012). The production of the northern Mediterranean (European countries) represents approximately 35% of the production in the basin (FAO, 2016). In Mediterranean fisheries, actions are urgently needed to reverse the unsustainable exploitation of most stocks (85% overexploited according to FAO, 2016). Fisheries management is based mainly on input control rules (i.e., capacity, selectivity, and effort limitations), whereas output control is applied on a few highly migratory stocks. The former approach requires a tiered control system, so it is possible that low compliance affected its effectiveness in regard to stock recovery in the Mediterranean (e.g., Damalas and Vassilopoulou, 2013). A cooperative approach, involving stakeholders with different backgrounds, could help to increase collective awareness of this issue. It is thus fundamental to facilitate good governance and policy implementation, reducing conflicts and distrust in the advice and decision-making processes (e.g., Delaney et al., 2007; Shelton, 2007; Linke et al., 2011).

The Reform of the Common Fishery Policy (CFP) (EU Reg. 1380/2013[1]) clearly places the role of stakeholders in a more interactive governance system, involving other actors besides scientists and policymakers. The Advisory Councils, established following the 2002 reform of the CFP, are currently the bodies where representatives from a broad set of stakeholders contribute to the decision-making process through a bottom-up approach (Aanesen et al., 2014).

However, participatory management requires that stakeholders are enabled to express their qualitative and quantitative perceptions about the current situation, being aware of the objectives and indicators used to assess the fishery's impact, the information these are able to convey, the advice procedures, and the range of applicable management options with estimates of their biological, economic, and social consequences. This is particularly relevant in the Mediterranean, where the structured participation of the stakeholders in the governance system is quite recent (Commission Decision 2008/695/EC[2]).

The scientific advisory process that supports the CFP commitments (e.g., Maximum Sustainable Yield, landing obligation, and EAFM, including Good Environmental Status according to the Marine Strategy Directive Framework[3]) is characterized by multiple attributes and objectives, involving the estimation of indicators associated with such specific objectives. Advice on the state of the stocks, fisheries, and ecosystems is the basis for the implementation of the Multiannual Management Plans (MAP), which are recognized as a more effective tool for achieving the multiple objectives of the CFP and thus for reversing the overexploitation status of several stocks while minimizing the economic and social impacts. Designing and evaluating MAPs is a complex task, which requires reliable data, specific expertise, and the involvement of stakeholders to share knowledge and improve the understanding of management measures while receiving feedback on management options and implementation strategies.

Multi Criteria Decision Analysis (MCDA; e.g., Belton and Stewart, 2002) is an area of growing interest in fisheries management, and there are several applications worldwide (e.g., Soma, 2003; Leung, 2006; Bevacqua et al., 2009; Innes and Pascoe, 2010; Aanesen et al., 2014; Kavadas et al., 2015; Rossetto et al., 2015). MCDA models are powerful for addressing specific problems characterized by multiple and often conflicting objectives, something that is common in fishery systems. However, only a limited portion of the applications reported in the literature has explicitly engaged stakeholders at any stage of the MCDA process (see Estévez and Gelcich, 2015 for a review). In addition, MCDA assessments can be affected by a range of uncertainties due to the imperfect knowledge of the specific system under study and the subjectivity of expert judgments (e.g., Banuelas and Antony, 2004; Rossetto et al., 2015). Incorporating uncertainty in the MCDA has been achieved using probabilistic judgments (e.g., Levary and Wan, 1998), fuzzy sets (Lee et al.,

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[1] *Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, Amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and Repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC Official Journal of the European Union*. Brussels.

[2] Commission Decision (2008/695/EC). *Commission Decision of 29 August 2008 Declaring Operational the Regional Advisory Council for Mediterranean Sea under the Common Fisheries Policy*.

[3] *Directive 2008/56/EC of the European Parliament and of The Council of 17 June 2008 Establishing a Framework for Community Action in the Field of Marine Environmental Policy (Marine Strategy Framework Directive), EU-COM*. Available online at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:164:0019:0040:EN:PDF)

2001), and ranking intervals (Arbel and Vargas, 1993) to test the statistical significance of the final score and to facilitate consensus when a large number of stakeholders is involved.

In this paper, we applied two preference modeling methods that allow the transformation of qualitative judgments into quantitative judgments in order to ease their evaluation and practical use: the Analytical Hierarchy Process (AHP) (e.g., Saaty, 1980, 2003, 2008) and the Non-Structural Fuzzy Decision Support System (NSFDSS) (Tam et al., 2002, 2006). AHP has, together with ordination techniques, the highest number of applications in fishery science (Leung et al., 1998; Mardle and Pascoe, 1999; Andalecio, 2010; Pascoe et al., 2014), while NSFDSS has not yet been applied to fishery case studies.

Both techniques are decision-aiding tools for resolving multi-criteria decision problems based on the decomposition into a hierarchy of smaller problems ranked through pairwise comparisons, evaluated according to a scale of semantic scores. AHP relies upon a broad range of scores, whereas NSFDSS is based on a simpler scoring scale, with only three possible options: 0.5 (x and y are equally important), 1 (x is more important than y), and 0 (x is less important than y). This simplification eases the expression of judgment, possibly reducing inconsistencies due to human uncertainty or inaccuracy. However, this simpler scoring is reclassified inside the model into a more broad scale, using fuzzy sets (assignment of priority scores; Chen, 1998). This feature, coupled with an internal checking, makes it possible, in addition, to solve the inconsistency issues that can only be measured in AHP trough a consistency ratio, e.g., an index developed as a guide for decision-makers (Saaty, 2008).

We applied the two methods, at a pilot scale, during an *ad hoc* workshop carried out in collaboration with the Mediterranean Advisory Council (MEDAC) to elicit the preferences of 12 stakeholders, with different backgrounds (fishermen, representatives of fisheries associations, and of non-governmental environmental organization), belonging to the MEDAC organization. The workshop aimed to make all stakeholders aware of the general definition and specific concepts of the surveys. During the workshop we applied: (i) AHP for exploring stakeholders' perceptions about the objectives and indicators used in the monitoring of stocks, ecosystems, and fisheries; and (ii) NSFDSS for gathering feedbacks regarding stakeholders' preferences on management options to improve fishery sustainability (e.g., reducing discards and improving the ecosystem state and economic yield in the long term).

MATERIALS AND METHODS

We implemented the AHP and the NSFDSS, respectively, in survey 1 and survey 2 to:

1. understand how stakeholders rank the importance of the economic, social, and biological factors affecting the fisheries;
2. evaluate how stakeholders rank the different indicators currently applied in the assessment of fishery impact;
3. quantify how stakeholders perceive a set of management options.

In both methods, the decision-making process needs to be decomposed to generate priorities in a specific way, defining the problem and structuring the decision hierarchy from the goal on top to the objectives at the intermediate level and down to the indicators/management options. Decision trees were thus identified for both survey designs.

During a dedicated workshop of MEDAC 12 equally weighed stakeholders (fishermen, representatives of fisheries associations and of non-governmental environmental organizations) were first informed about the survey objective, and then they were invited to interact in the plenary discussion; finally, they were asked to fill in two different questionnaires for the two surveys. MEDAC is a non-profit organization representing the fisheries sector (including the industrial fleet, small-scale fisheries, the processing sector, and trade unions) and other interest groups, such as, environmental organizations, consumer groups, and sports/recreational fishery associations, operating in the Mediterranean area in the framework of the CFP (http://en.med-ac.eu/chi_siamo.php).

The administration of the questionnaires followed a broad discussion on the objectives of the survey, problem structure, survey structure, and technical issues. Ethics approval was not required for this study as per institutional guidelines and Italian law and regulations. In compliance with the aforementioned guidelines, laws, and regulations, oral informed consent was obtained from the participants. Their answers were anonymized, and it is not possible to link the statements back to individual subjects.

Survey 1 (AHP)

The goal has been defined as "*Contribute to a sustainable fishery management*" in line with the CFP main target. Three main components were considered: *Ecological state*, *Pressure/impact*, and *Economic state*. Then, the hierarchic processes for the classification of the objectives and the *associated* indicators were defined (decision tree in **Figure 1**).

In the AHP survey the preferences were expressed according to a scale of semantic scores from 1 to 5 (**Table 1**). In a pairwise comparison, the respondents were asked to evaluate the importance of one objective against another, with the value "1" representing equal importance. The stakeholders expressed their degree of preference between two alternatives (see questionnaire 1 in Supplementary Material), with the higher score indicating the higher preference.

The results were elaborated using a pairwise comparison matrix $A = \left(a_{i,j}\right)_{i,j=1,2,...N}$, where N is the number of alternatives (objectives or indicators) and $a_{i,j}$ is the score assigned by the stakeholder in the pairwise comparison between the *i-th* and *j-th* alternatives. A is a positive reciprocal square $N \times N$ matrix, where a square matrix is reciprocal if $a_{i,j} = \frac{1}{a_{j,i}}$. Further, we computed the weight vector in each level of the hierarchical tree through the eigenvalue/eigenvector averaging technique, according to Saaty (2003, 2008), who demonstrated that a good approximation of the priority vector is represented by the principal eigenvector of A. The eigenvector was then normalized to obtain a priorities' vector for each pairwise comparison matrix.

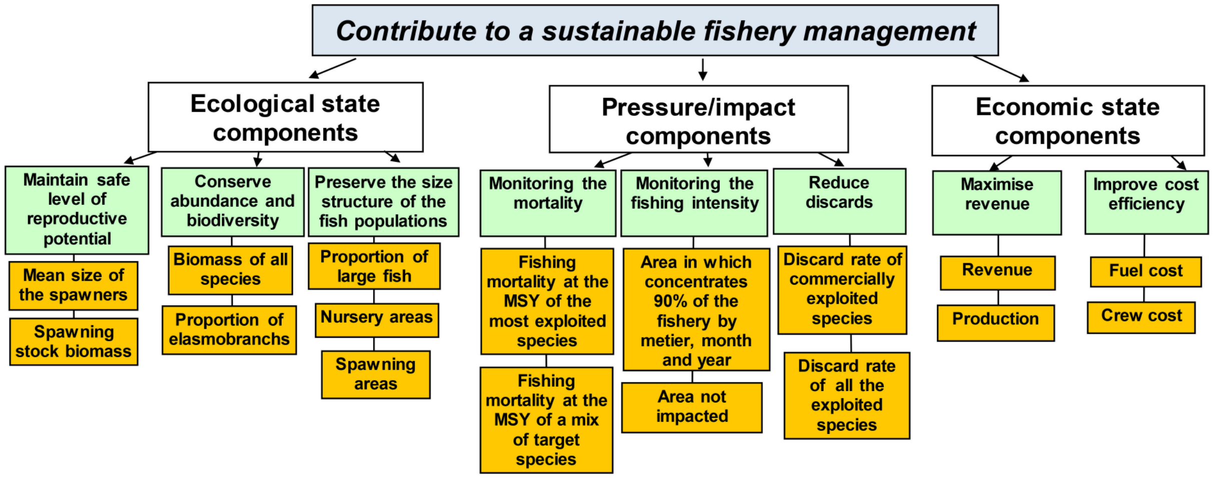

FIGURE 1 | Decision Tree of survey 1. The AHP decision tree, indicating the goal, the three main components (ecological, pressure, and economic), and objectives (1st level green cells) with associated indicators (2nd level yellow cells).

TABLE 1 | Scale of semantic operators and relative score adopted in survey 1.

Semantic score for importance	Numerical score
Equally important	1
Little more important	2
More important	3
Much more important	4
Exceptionally more important	5

The principal eigenvalue (or its multiple) λ_{max} is associated to the principal eigenvector, and it is used to estimate the consistency of the answers.

It was possible to calculate a measure of consistency (Consistency Ratio) for each matrix of preferences using the following formula: $CR = \frac{CI}{RI} = \frac{\frac{\lambda_{max}-N}{N-1}}{RI}$, where CI is the consistency index, computed using the principal eigenvalue λ_{max} and the number of alternatives N; the random index RI is a randomly generated value, computed assuming that the numbers in pairwise comparison matrix A are completely random (Saaty, 2008).

In this survey a questionnaire with 38 pairwise combinations was tested: 28 combinations were related to the objectives and 10 to the indicators (see questionnaire 1 in the Supplementary Material).

Survey 2 (NSFDSS)

The survey 2 has the same goal of survey 1, while the three components are *ecological*, *economic*, and *social*. Within this framework the objectives that can drive the choice about the possible alternative management options have been identified as in the decision tree reported in **Figure 2**.

In the NSFDSS approach the management options were compared pairwise against each of the seven objectives. Hence, pairwise comparisons were also made among objectives (see questionnaire 2 in the Supplementary Material). The final step was the synthesis of priorities.

We recorded stakeholders' preferences in each pairwise comparison matrix $A = \left(a_{i,j}\right)_{i,j=1,2,\ldots N}$, where N is the number of alternatives (objectives or management options). Then we filled the whole matrix, making a check of consistency of preferences, as follows:

$$if \begin{cases} a_{i,j} = 1 \Rightarrow a_{j,i} = 0 \\ a_{i,j} = 0 \Rightarrow a_{j,i} = 1 \\ a_{i,j} = 0.5 \Rightarrow a_{j,i} = 0.5 \end{cases}$$

Summing up the values on each row of the matrixes, the management options are rearranged in descending order with respect to each objective. With an analogous procedure, the objectives are rearranged in descending order. Based on this priority order, we assigned a semantic operator to each alternative by comparing it to the one with the highest value. Chen (1998) incorporated fuzzy set theory to the model, as described by Tam et al. (2002). Thus, each semantic operator is assigned to a semantic score within the range [0, 1]. After obtaining the priority order of the management options, it is necessary to measure the magnitude of the pairwise comparison by calculating the weights w_i of the objectives, obtained normalizing the associated semantic scores. Multiplying the weights of management options by the corresponding weights of the objectives, three matrices are obtained: products, square products, and the complementary square matrices. These three matrices are necessary in order to compute the final priority vector of decisions (management options), applying the Hamming (1950) distance:

$$u_j = \frac{1}{1 + \left\{ \frac{\sum_{i=1}^{N} \left[w_i (r_{i,j} - 1)^p\right]}{\sum_{i=1}^{N} (w_i r_{ij})^p} \right\}^{2/p}},$$

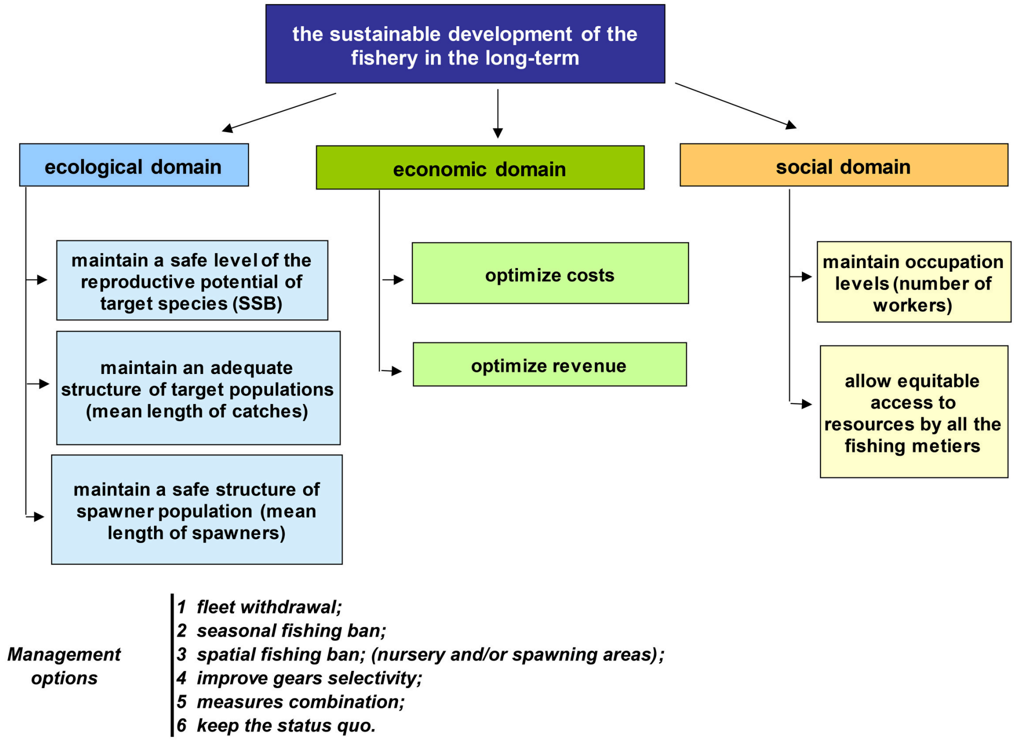

FIGURE 2 | Decision Tree of survey 2. The NSFDSS decision tree, indicating the goal, the three main components (ecological, economic and social), the objectives, and the management options.

where w_i is the weight of each objective, $r_{i.j}$ is the semantic score (Chen, 1998), and N is the number of objectives. The final priority vector was obtained taking the average of the two values of u_j (for $p = 1$ and for $p = 2$).

In this survey a questionnaire with 136 pairwise combinations was tested, with 115 of these comparing the management options and 21 the objectives (see questionnaire 2 in the Supplementary Material).

Sensitivity

A sensitivity analysis was carried out to evaluate the robustness of the results, with respect to the uncertainty associated to the weights expressing the relative importance of the elements considered both in the AHP and in the NSFDSS. To this end, the Monte Carlo approach was applied to both analyses, according to the following steps:

1. Application of uncertainty to the normalized vector of weights at each hierarchical level for each stakeholder, multiplying the deterministic local weights by the factor $(1 + \varepsilon)$, where ε is a normally distributed error with mean 0 and standard deviation 0.15 (so that 90% confidence bounds encompass the original value of the weight ±20%). A total of 1,000 extractions were made;
2. The perturbed local weights were normalized to add up to 1;
3. On the 1,000 vectors of weights for each hierarchical level, and for each element, relevant percentiles (0.05, 0.25, median, 0.75, 0.95) and statistics (minimum, maximum, mean, standard deviation and CV) were calculated;
4. For each statistic and percentile, the corresponding global vector was derived as a geometric mean among all stakeholders; this was carried out at each level of the hierarchical tree.

Estimates

First, an *exploratory analysis* on the perturbed weight vectors was carried out to detect possible differences between rankings. For each hierarchical level of the decision tree a global frequency was computed, taking all the runs of all the stakeholders as a whole and estimating the frequency to be the first, the second, etc. on the total perturbed rankings. This frequency has been interpreted as a proxy of the probability to get the higher preference, that is, a synthesis of the frequency of the ranking for a given objective/indicator, based on its weight and taking into account the judgment of each stakeholder (empirical probability). The results of this exploratory analysis are affected by both the uncertainty introduced in the process and the natural variability among the stakeholders' preferences. Then, *ranking preferences* over stakeholders were estimated using geometric means for both surveys. These global means and other associated statistics are only affected by the uncertainty introduced in the process, as the variability due to the different perceptions of stakeholders is smoothed by the mean.

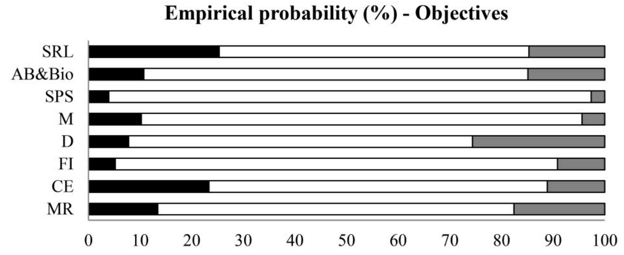

FIGURE 3 | Survey 1—AHP (Exploratory analysis): empirical probability to be first and to be last associated to the objectives according to stakeholders' preferences, respectively, for ecological, pressure/impact, and economic components. SRL, Maintain safe level of reproductive potential; AB&Bio, Conserve abundance and biodiversity; SPS, Preserve the size structure of the fish populations; M, Monitoring the mortality; D, Reduce discards; FI, Monitoring the fishing intensity; CE, Improve cost efficiency; MR, Maximize revenue.

All the algorithms and computations were performed using an *ad hoc* routine developed in R language.

RESULTS

Survey 1

Exploratory Analysis

The objective to "*maintain a safe level of reproductive potential*" had the maximum empirical probability to be ranked first (25.32%), followed by *improve cost efficiency* (23.35%). The other objectives of the ecological and economic components received an intermediate or very low empirical probability. Among the objectives pertaining to the pressure component *Monitoring the mortality* reached a higher value compared to the other two objectives, while *reduce discards* had the higher probability to be ranked the last (25.61%; **Figure 3**).

The empirical probability associated to the indicators showed that the *fuel cost* had the highest probability to be the most important (31.59%), while the indicator *proportion of large fish* reached the highest probability to be ranked the least important (28.59%; **Figure 4**). However, for the ecological component the *biomass of all the species* achieved a higher empirical probability compared to the other indicators, whereas for the impact component the indicator *Fishing mortality at the MSY of the most exploited species* achieved a higher value.

The Consistency Ratios were generally satisfactory and below 0.1 (a value suggested as a threshold by Saaty, 2008), except in two cases.

Ranking Preferences

The average statistics of preferences expressed by stakeholders for the objectives and indicators highlighted higher scores (**Figure 5** and **Table 2**) for the objective *maintain a safe level of reproductive potential* (0.13), pertaining to the ecological component, and the lowest for the objective of the pressure/impact component *reduce discard* (0.08). The other objectives achieved a similar score (0.10–0.11). Likewise, in the exploratory analysis, the objective *improve cost efficiency* of the economic component received a higher preference compared to *maximize the revenue*.

With regard to the stakeholders' perception of the effectiveness of each indicator to track ecological objectives, a higher rank was attributed to *biomass of all species* (score = 0.069), *mean size of the spawners* (0.064), and *spawning stock biomass* (0.059), while the *proportion of large fish* was considered the less important indicator, consistent with the exploratory analysis. Among the pressure/impact indicators, the stakeholders' preference was expressed for *fishing mortality at the MSY of a mix of target species* (0.054), while *fishing mortality at the MSY of the most exploited species* received lower preferences (0.037). This result, which appears inconsistent with the exploratory analysis, is a sign of skewed stakeholder responses. Among the economic components, the *fuel cost* received the highest score (0.07), as in the exploratory analysis (**Figure 5** and **Table 2**).

Survey 2

Exploratory Analysis

The objective, in the ecological domain, that had the highest empirical probability to be the most important for the sustainable development of the fishery in the long term was *maintain a safe level of the reproductive potential of target species* (25%). Likewise, *optimize revenue* and *maintain occupation levels* had the highest empirical probability to be the more important, respectively in the economic and social domains. The highest probability to be the least important (33.33%) was obtained by *allow equitable access to resources by all the fishing métiers*, belonging to the social domain (**Figure 6**).

Among the management options, *measures combination* (47.77%) obtained the highest empirical probability to be ranked the first option, while *fleet withdrawal* (57.98%) was ranked the least appropriate option, followed by *keep the status quo* (41.34%; **Figure 6**).

Ranking Preferences

Likewise, in the exploratory analysis, in the ranking preferences of objectives (**Figure 7**), stakeholders assigned the higher score to *maintain occupation levels* (0.16) and the lower score to *allow equitable access to resources by all the fishing métiers* (0.11). Intermediate scores (0.14) were assigned to the other objectives of the ecological and economic components: i.e., *optimize revenues*, *optimize costs*, *maintain safe level of the reproductive potential of target species*, and *mean length of spawners*.

In the ranking preferences of management options (**Figure 7**), stakeholders considered the *measures combination* as the best option to achieve sustainable fishery management in the long term (score = 0.89), followed by the *spatial fishing ban* (0.86) and the *seasonal fishing ban* (0.75). The last choices were *keep status quo* (0.47) and *fleet withdrawal* (0.40).

DISCUSSION

Preference modeling methods, particularly those using multi-attribute value theory, are well suited in situations where the active involvement of stakeholders is desired in the entire decision-making process. Participative MCDA is progressively

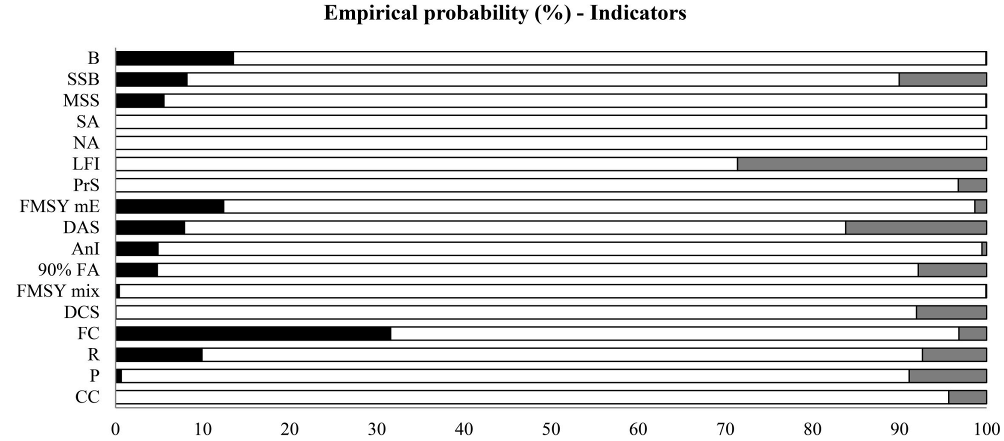

FIGURE 4 | Survey 1—AHP (Exploratory analysis): empirical probability to be first and to be last associated to the indicators according to stakeholders' preferences, respectively, for ecological, pressure/impact, and economic components. B, Biomass of all species; SSB, Spawning stock biomass; MSS, Mean size of the spawners; SA, Spawning areas; NA, Nursery areas; LFI, Proportion of large fish; PrS, Proportion of elasmobranchs; F_{MSY} mE, Fishing mortality at the MSY of the most exploited species; DAS, Discard rate of all the exploited species; AnI, Area not impacted by fishing gears; 90% FA, Area in which 90% of the fishery by metier, month, and year concentrates; F_{MSY} mix, Fishing mortality at the MSY of a mix of target species; DCS, Discard rate of commercially exploited species; FC, Fuel cost; R, Revenue; P, Production; CC, Crew cost.

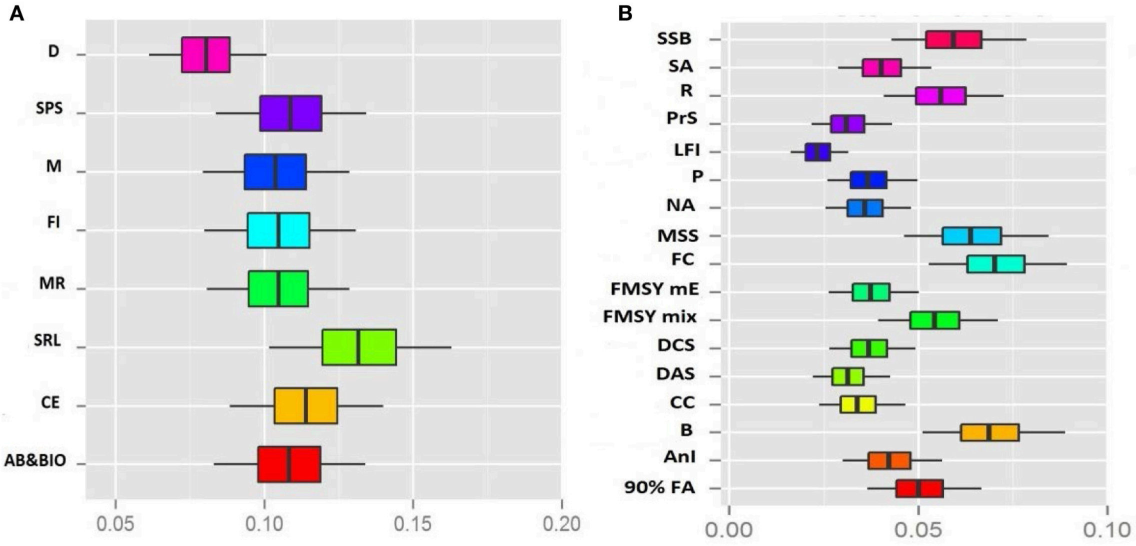

FIGURE 5 | Survey 1—AHP (Ranking preferences): Ranking the objectives with uncertainty (box plot with median and percentile values: 0.05, 0.25, 0.75, and 0.95). **(A)** Level 1, D, Reduce discards; SPS, Preserve the size structure of the fish populations; M, Monitoring the mortality; FI, Monitoring the fishing intensity; MR, Maximize revenue; SRL, Maintain safe level of reproductive potential; CE, Improve cost efficiency; AB&Bio, Conserve abundance and biodiversity. **(B)** Level 2, SSB, Spawning stock biomass; SA, Spawning areas; R, Revenue; PrS, Proportion of elasmobranchs; LFI, Proportion of large fish; P, Production; NA, Nursery areas; MSS, Mean size of the spawners; FC, Fuel cost; FMSY mE, Fishing mortality at the MSY of the most exploited species; FMSY mix, Fishing mortality at the MSY of a mix of target species; DCS, Discard rate of commercially exploited species; DAS, Discard rate of all the exploited species; CC, Crew cost; B, Biomass of all species; AnI, Area not impacted by fishing gears; 90% FA, Area in which 90% of the fishery by metier, month, and year concentrates.

applied in marine multi-objective management situations, and it is of increasing interest in fisheries management, aquaculture, and marine conservation, although the engagement of stakeholders is often limited to certain steps in the whole process (e.g., Estévez and Gelcich, 2015). We tested this methodological approach, which is a novel application to a Mediterranean case study, at a pilot scale to support a participatory procedure and elicit stakeholders' preferences as a step toward understanding and incorporating their knowledge and views. This kind of process is expected to contribute to effective fisheries management in terms of agreement on specific objectives and measures.

TABLE 2 | Survey 1 (Ranking preferences).

Component	Objectives	Indicators	Perc_0.05	Median	Perc_0.95
Ecological	Maintain safe level of reproductive potential	1. Spawning stock biomass	0.043	0.059	0.078
		2. Mean size of the spawners	0.046	0.064	0.084
	Conserve abundance and biodiversity	3. Biomass of all species	0.051	0.069	0.089
		4. Proportion of elasmobranchs	0.022	0.031	0.043
	Preserve the size structure of the of fish populations	5. Proportion of large fish	0.016	0.023	0.032
		6. Nursery areas	0.025	0.036	0.048
		7. Spawning areas	0.029	0.040	0.053
Pressure/impact	Monitoring the mortality	8. Fishing mortality at the MSY of the most exploited species	0.026	0.037	0.050
		9. Fishing mortality at the MSY of a mix of target species	0.039	0.054	0.071
	Monitoring the fishing intensity	10. Area not impacted by fishing gears	0.030	0.042	0.056
		11. Area in which concentrates 90% of the fishery by métier, month, and year	0.036	0.050	0.067
	Reduce discards	12. Discard rate of commercially exploited species	0.026	0.037	0.049
		13. Discard rate of all the exploited species	0.022	0.031	0.042
Economic	Maximize revenue	14. Revenue	0.041	0.056	0.073
		15. Production	0.026	0.037	0.050
	Improve cost efficiency	16. Fuel cost	0.053	0.070	0.089
		17. Crew cost	0.024	0.034	0.047

Geometric means (5th, median, and 95th percentile) of indicator weights classified by objective and component.

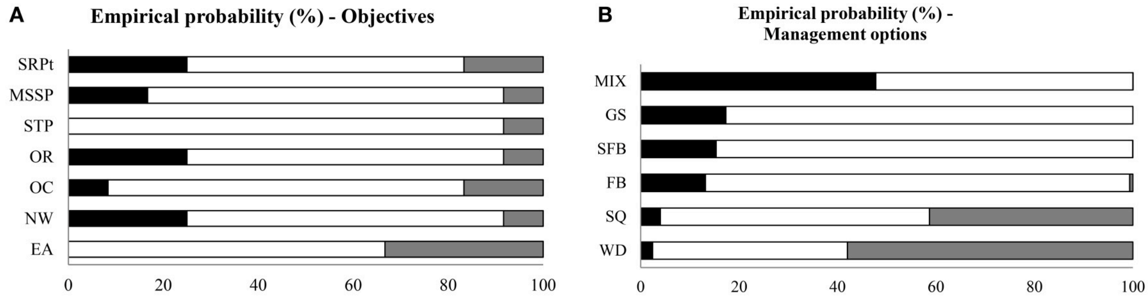

FIGURE 6 | Survey 2—NSFDSS (Exploratory analysis): empirical probability to be first and to be last associated to **(A)** objectives and **(B)** management options, according to stakeholders' preferences, respectively, for ecological, economic, and social components. **(A)** SRPt, Maintain a safe level of the reproductive potential of target species; MSSP, Maintain a safe structure of spawner population; STP, Maintain an adequate structure of target populations; OR, Optimize revenue; OC, Optimize costs; NW, Maintain occupation levels; EA, Allow equitable access to resources by all the fishing metiers. **(B)** MIX, measures combination; GS, improve gears selectivity; SFB, spatial fishing ban; FB, seasonal fishing ban; SQ, keep the status quo; WD, fleet withdrawal.

Information on the management and socio-economic aspects of fisheries is relatively limited in the Mediterranean and Black Seas, where there is a need for more integration of the ecosystem and socio-economic considerations into assessment procedures (Sartor et al., 2014). Full stakeholders' engagement is thus pivotal to promote tools for developing effective fisheries co-management, evolving toward an assessment of fisheries systems rather than fish stocks. Following Halls et al. (2005), such an approach can make a broader use of traditional ecological knowledge and propose co-management initiatives in data collection methods, especially for small scale fisheries.

We explored the preferences of 12 stakeholders answering to two surveys in a meeting organized by MEDAC, applying AHP and NFSDSS methods. With the former method we elicited the stakeholders' perceptions about the objectives and indicators used for stocks, ecosystem, and fisheries monitoring. Whereas, using the latter method we elicited the stakeholders' preferences about management options to improve fishery sustainability.

Regarding the AHP, which is used in a very wide range of areas with complex decision and evaluation problems (Andalecio, 2010; Kavadas et al., 2015; Rossetto et al., 2015), we identified clear benefits such as eliciting priorities among stakeholders

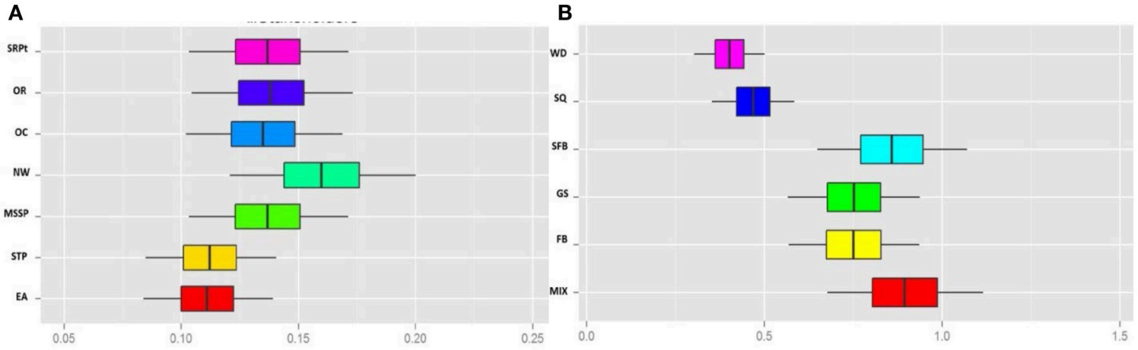

FIGURE 7 | Survey 2—NSFDSS (Ranking preferences): **(A)** ranking objectives and **(B)** management options, according to stakeholders' preferences with uncertainty (box plot with median and percentile values: 0.05, 0.25, 0.75, and 0.95). **(A)** SRPt, Maintain a safe level of the reproductive potential of target species; OR, Optimize revenue; OC, Optimize costs; NW, Maintain occupation levels; MSSP, Maintain a safe structure of spawner population; STP, Maintain an adequate structure of target populations; EA, Allow equitable access to resources by all the fishing metiers. **(B)** WD, fleet withdrawal; SQ, keep the status quo; SFB, spatial fishing ban; GS, improve gears selectivity; FB, seasonal fishing ban; MIX, measures combination.

and taking responsibilities (Nielsen and Mathiesen, 2006). AHP is also an empowering, communicating, and quantifying tool that may allow stakeholder engagement, which is usually omitted from the formal decision-making process (Leung, 2006; Brooks et al., 2015). In addition, this technique acknowledges that decision-makers may be much more comfortable in expressing semantic evaluations (e.g., equal important, much more important, etc.) and using pairwise comparisons rather than expressing attributes only in terms of numerical scores. It is worth highlighting that in our case we observed a satisfactory consistency ratio for 10 out of 12 stakeholders interviewed. In addition, excluding the two respondents with a consistency ratio slightly above the threshold value from the AHP analysis did not affect the results.

However, users of this technique have pointed out some weaknesses, with criticisms focused on the structuring of the hierarchy process, the inconsistent ranking of preferences, and the lack of a pre-defined approach for the combination of judgments. Despite its simplicity AHP is considered to be a powerful and versatile technique with merits related to both the involvement of stakeholder groups in the decision-making process and the advantageous features of the method as a communication tool (Soma, 2003).

An advantage of using NFSDSS, compared to similar methods such as AHP, is the major accuracy of the solution due to the automatic consistency checking (Tam et al., 2006). In addition, NFSDSS takes advantage of the fuzzy set theory using semantic operators to allow the improvement of expert judgment analysis (Tam et al., 2002). This leads to a further strength, as stakeholders have only three possible answers to give: prefer A to B, prefer B to A, or A and B are equally important. This simplifies the decision-making process and may reduce errors. Despite these advantages, NSFDSS, given the simplification of the questions, may sometimes lead to a reduction of the differentiation between decisions, making the selection of the best option difficult (Tam et al., 2006).

Basically, the pilot scale surveys we carried out demonstrated the suitability of both the MCDA methods, even in the light of their pros and cons.

The proposed case studies seemed feasible and conducive for stakeholders' engagement at the level of the fishing industry and non-governmental organizations (NGOs), that are members of the MEDAC. Overall, the exploratory analysis and the ranking preferences gave consistent results and showed a low level of skewness in the opinions expressed by the participants in the surveys, even though the group composition mirrored the presence of stakeholders with different backgrounds, as represented in the MEDAC. This allowed us to neglect the analysis by group, treating all the stakeholders as belonging to the same group.

Looking into the results of the surveys, it emerged that the opinions of different stakeholders linked to key issues of fisheries' sustainability (e.g., improving ecosystem state and yield in the long term, avoiding bycatches, and reducing discards) converged toward preferences for ecological state objectives, such as, *maintain a safe level of reproductive potential,* and for economic state objectives, such as, *improve cost efficiency*. The latter received a higher preference compared to the counterpart economical state objective *maximize the revenue*, while the lowest score was assigned to the objective of the pressure/impact component *reduce discard*. This result demonstrates the awareness of the key role of ecological objectives, as in Janssen et al. (2014), and also reflects the common sense of fishermen, who generally consider the spawners as the more fragile component of the stock, which necessitates protection. This is quite different from the results of Aanesen et al. (2014), who found a low interest of the industry in fostering ecological objectives.

Regarding the economic state, it was unsurprising that stakeholders considered the objective of *improve cost efficiency* more effective for increasing profit, given that possible limitations of effort and catches would make it more difficult to *maximize revenues* if cost efficiency and marketing of the fish products are not improved. The low level of preference assigned to *reduce discard* might be due to the perception of this objective as a further burden, considered difficult to put in practice in the short term in the multispecies–multitarget Mediterranean fisheries.

Indicators are commonly used in the communication between scientific researchers and managers as synthetic tools to monitor the stocks, the fleet, as well as the ecological state of marine resources. Each indicator is generally defined with the aim to control the achievement of a specific objective, while all the objectives concur to the attainment of the main goal (i.e., contributing to sustainable fishery management). The role of such indicators is crucial because they make it possible to describe the current situation of the fishery system and to foresee the impact of alternative management measures through the use of *ad hoc* bio-economic simulation models (e.g., Bevacqua et al., 2009; Johnston et al., 2010; Spedicato, 2016; Russo et al., 2017). Nevertheless, the understanding of these indicators is not always straightforward for the stakeholders, who are not fully involved in the advice process. Moreover, their practice and solid knowledge of the aspects linked to the fishery sector would have the potential to streamline the management process, improving the level of compliance to the management measures.

A glance into the ranking of the indicators (survey 1) shows that the economic and ecological ones occupy the top five places in the list. In particular, the decisive importance that stakeholders assign to *fuel costs* in determining the cost-effectiveness of fisheries is clear, which is consistent with the first-level objective *improve cost efficiency*. After that, we find three indicators (*biomass of all species*, *mean size of the spawners*, and *spawning stock biomass*), all belonging to the ecological component, which highlight the importance that stakeholders assign to monitoring the reproductive potential and stock abundance. Low interest is expressed for the indicator linked to the fish community structure, the *Large Fish Indicator (LFI)*, which is related to the ecosystem state, but this is counterbalanced by the interest for the indicator *biomass of all the species*. The reason may be that the latter is more understandable and even easier to communicate than the former.

As in Prigent et al. (2008) we observed that the ecological indicators used by the fishermen as the basis to form their opinions were quite similar to those generally used by scientists for assessing the state of exploited marine populations and communities.

Overall, the results of the second-level objectives are quite in line with those of Aanesen et al. (2014), who observed that stakeholders belonging to the fishing industry ranked as first the economic objectives, which highlights the stakeholder's attitude to consider unrealistic achieving the objective of the biological resources sustainability without social and economic sustainability.

With regards to the economic indicators, stakeholders gave higher priority to *revenue* in comparison to production, which is a sign of awareness that increasing fish *production* does not necessarily turn into increased revenue, and they gave higher priority to *fuel costs* in comparison to *crew costs*. This is because fuel is one of the more significant variable costs in the fishing industry.

In addition, it is worth noting that the pressure/impact indicators always occupy a low rank position. Consistently with the value assigned to the first-level objectives, the indicators *discard rate of commercially exploited species* and *discard rate of all the exploited species* were considered less important compared to the ecological state and economic indicators.

As observed by Innes and Pascoe (2010), a lower relevance was given to *Discard rate of commercially exploited species*. Conversely, higher preferences were given to the ecological indicators, indicating that stakeholders focus more on population state indicators than on impact indicators, as also pinpointed by Nielsen and Mathiesen (2006) in an AHP application.

Among the pressure/impact indicators, only *Fishing mortality at the MSY of a mix of target species* reached a high priority level, probably because stakeholders perceive the need to account for the complexity of the ecosystem in terms of the number of species and their interactions rather than referring to a single stock.

Interestingly, the aggregated preferences of alternative management measures (survey 2) ranked against the objectives showed that the perceptions of the objectives were consistent with the results of survey 1, prioritizing the ecological objective *Maintain a safe level of the reproductive potential of target species* and the economic objective *Optimize revenues*. There was, however, a social concern, which is underpinned by the priority assigned to the objective *Maintain occupation levels*. This is clearly indicative of an individual perspective, as the objective *Allow equitable access to resources by all the fishing metiers* received one of the lowest scores, testifying to the peculiar aspect of highly competitive fishermen's behavior. Consistent with survey 1, objectives such as, *Maintain an adequate structure of target populations* received the least interest, confirming the difficulties in perceiving/understanding the consequences of fishery impact in terms of erosion of age/length groups from harvested populations.

Considering management options, the *measures combination* was ranked as the first option while *spatial fishing ban* was second. The worst option for stakeholders was scrapping of the fleet, likely showing that most of them have not yet lost hope that the fisheries could produce income, if the exploitation of the resources is sustainable. Moreover, the very low ranking of *keep the status quo* shows awareness that the current state of exploitation can hardly be sustained in the long run. Less consideration was given to the management strategy *improve gear selectivity*, which seems to reflect the view that selectivity measures alone are not very effective for the Mediterranean mixed fisheries. It is interesting to note that the *spatial fishing ban* was preferred to the *seasonal fishing ban*, which could be interpreted as showing greater confidence in the positive effect of protecting only some essential fish habitats, such as, spawner/nursery areas, in comparison to a *seasonal fishing ban* extended to all the areas. This is probably because spatial fishing bans leave room for the idea that some fishing activities in areas other than those that are protected could be allowed throughout the year. This would contradict to a certain extent the reluctance of stakeholders to establish marine protected areas, which was reported by Jentoft et al. (2012), who pinpointed fishermen's concerns about such spatial measures, based on the perceived risk of reduced operational flexibility and an imbalance between gains and losses. On the other hand, even in the present study, the high interest expressed toward *spatial fishing ban* is not corroborated by the priority assigned to indicators such as, the presence of *spawning* and *nursery areas*, which received a low rank in survey 1. This apparent contradiction could be a consequence of the range of indicators proposed, which led to higher ranks for those that were easier to interpret and, to a certain extent, also to the broader scale of semantic operators (5 possibilities) used in AHP. The preference of one management strategy compared to another one (e.g., the *spatial fishing ban* vs. *seasonal fishing ban*) is an aspect that is often neglected, but it represents important information that is useful for managers in the preparation of MAPs. Indeed, the reduction in the fishing pressure and especially the change of the exploitation patterns (increased size/age at first capture) for restoring the overexploited stocks and achieving the maximum sustainable yield (MSY) are pivotal for the implementation of the new CFP objectives. Gear selectivity has been considered insufficient or inadequate to reduce the fishing mortality on the fisheries' recruits (e.g., Suuronen, 2005). Seasonal fishing bans have been applied in the European Mediterranean countries (e.g., Greece and Italy), but they have not effectively mitigated the overexploitation of stocks, especially those mainly distributed offshore.

MCDA assessments can, however, be affected by a range of uncertainties due to the imperfect knowledge of the specific system under study, the subjectivity of expert judgments, unfamiliarity with the elicitation process, a large number of pairwise comparisons, incomplete information or knowledge, uncertainty about the outcome of events, or levels of intensity associated with stakeholder preferences (e.g., Banuelas and Antony, 2004; Rossetto et al., 2015).

In this study we addressed uncertainty issues, applying a probabilistic approach via the propagation of a normal error from the individual rankings to the synthetic rankings. Consequently, accounting for uncertainty allowed more appropriate rankings among objectives, indicators, and management options. Indeed, in our survey, a sensitivity analysis was carried out to evaluate the robustness of the results, with respect to the uncertainty associated to the weights expressing the relative importance of the elements considered in the AHP and NSFDSS. This approach is similar to the one used in Rossetto et al. (2015) and differs from the probabilistic judgments method described in Banuelas and Antony (2004), as the present work multiplicatively applies a normal distributed error to the deterministic eigenvector (in AHP) and to the objectives and management options priority vectors (in NSFDSS) to obtain the perturbed rankings.

Increased stakeholder participation and their knowledge integration are suggested to improve the EU's CFP, which is suffering from legitimacy, credibility, and compliance problems (Linke et al., 2011). The present work has made it possible to test a framework for the creation of synergies and to find common ground for a bottom-up approach in a transparent way. Two MCDA methods have been applied and proven useful for eliciting stakeholders' view on the potential effects of key issues on the economic and environmental sustainability of fisheries; for example, improving ecosystem state and yield in the long term, avoiding by catches and reducing discards, changing technical features of the gears, facing possible losses in the short term, and changing/releasing local seafood traditions/habits. The results suggest that, according to the preferences of the interviewed stakeholders, management measures aimed at reducing the environmental impacts of fishing that are more broad than simply discarding could be appropriate and sharable. In addition, to improve stakeholders' participatory role, there is a need for continuous cycles of planning, implementation, and adjustment due to the inherent complexity of monitoring fisheries, as well as the uncertainty of the fishery management process. At the same time, the ability to understand the concerns of managers (regulatory aspects, control issues, time-lines, political dimension, etc.), scientists (data availability, knowledge on species biology, population dynamic, etc.), and fishermen (practices, lifestyle, language issues, etc.) is key to ensuring a smooth process and the successful preparation and implementation of MAPs.

AUTHOR CONTRIBUTIONS

Substantial contributions to the conception or design of the work: GL, MTS, JB, VV, MS, and TG. Acquisition, analysis and interpretation of data: IB, GL, MTS, and MF. Drafting the work: GL, IB, and MTS. Revising the work critically for important intellectual content: GL, JB, IB, MF, TG, MS, VV, and MTS. Final approval of the version to be published: GL, JB, IB, MF, TG, MS, VV, and MTS. Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved: GL, JB, IB, MF, TG, MS, VV, and MTS.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2017.00328/full#supplementary-material

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Local Ecological Knowledge Indicates Temporal Trends of Benthic Invertebrates Species of the Adriatic Sea

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In the Adriatic Sea, shifts in benthic community structure have been attributed to multiple stressors, from the effects of climate change to the impacts of commercial fishing. Some fishing practices, such as bottom trawling, have caused a widespread decline in exploited fish stocks. Bottom trawling is also expected to have negative impacts on benthic habitats, usually structured by and hosting a large array of invertebrate species, which provide important ecological services to fish and commercial invertebrate stocks. However, in contrast to commercial species for which long-term time series of the abundance exist, data on these habitat-forming invertebrates are scarce, as they are usually caught as bycatch and discarded. Therefore, there is great uncertainty about their long-term trends, and if these populations are stable or declining. Here we used interview surveys conducted with bottom-trawling fishers of the central Adriatic Sea to gather local ecological knowledge on megabenthos abundance occurring in their fishing domain, as an alternative source of information to conventional fisheries data. We interviewed 44 fishers, from the most important ports of the Marche region of Italy, to understand how megabenthic species have changed in abundance within the area since the 1980s. Specifically, we asked fishers to provide qualitative abundance scores for 18 invertebrate species in five phyla (Porifera, Cnidaria, Bryozoa, Mollusca, and Echinodermata) based on their recollection of these species' presence in bycatch. We stratified responses in homogeneous temporal periods and geographic sectors of the study area, and analyzed their response with mixed effect ordered logistic regression models in order to evaluate spatiotemporal changes in the perceived abundance of each species. Our analysis suggests that the abundance of the sponge *Geodia cydonium*, the molluscs *Pecten jacobaeus*, *Atrina fragilis, Neopycnodonte cochlear,* and the group of holothurians, have declined. From fishers' perceptions, only the bryozoan *Amathia semiconvoluta* has increased. Local ecological knowledge can provide important information on environmental change and can highlight species and ecosystems at risk when conventional scientific data are scarce or absent. This approach can be expanded to other regions of the Adriatic and broader Mediterranean Sea to reconstruct change of this heavily exploited marine region.

Keywords: Adriatic Sea, local ecological knowledge, megabenthic species, historical trends, fishers perceptions

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INTRODUCTION

Marine ecosystems are subject to escalating pressure from the cumulative impact of multiple anthropogenic stressors (e.g., pollution, eutrophication, ocean acidification, and fishing), causing biodiversity loss, habitat degradation, and stock declines (Halpern et al., 2008, 2015; Coll et al., 2012; Micheli et al., 2013a). Fishing activities, in particular those employing non-selective gear such as bottom trawling and drift nets, are considered one of the most important anthropogenic sources of marine ecosystem decline, causing both direct (crushes and buries marine animals) and indirect (sediment removal, alteration of water-column fluxes, reduction of the original complexity of fishing grounds) impacts on marine populations and habitats (Watling and Norse, 1998; Jackson et al., 2001; Puig et al., 2012). These impacts are evident in the Mediterranean Sea, which combines a long history of exploitation with a high level of social, economic, and political complexity that present major challenges for effective marine management and conservation (Coll et al., 2012; Micheli et al., 2013a,b). To date, 85% of assessed Mediterranean stocks are overfished (Colloca et al., 2013), and current fisheries management is considered inadequate (Fouzai et al., 2012). The management strategies adopted in the Mediterranean basin largely take a single species approach instead of an ecosystem-base management approach (de Juan et al., 2012). Most regulations are aimed at reducing fishing effort and fishing capacity, and/or at implementing technical measures such as the regulation of mesh size, the establishment of a minimum landing size, and temporal, mostly seasonal fishing closures (de Juan et al., 2012; Fouzai et al., 2012; Colloca et al., 2013). However, scientific advice is rarely used to implement the spatial and temporal fisheries management strategies needed to achieve sustainable yields and to preserve the ecological role of the exploited species and their habitats (Colloca et al., 2013).

A major shift in management focus has occurred over the last 10 years through an increased awareness of the fundamental role played by habitat in fished stocks conservation and recovery, which has, in turn, led to the key concepts of Vulnerable Marine Ecosystems (VMEs) and Essential Fish Habitats (EFHs) (UNGA, 2006; FAO, 2009). VMEs and EFHs include both water column and sea bottom areas that support the productivity of commercial species and that are vulnerable to human activities, in particular to bottom trawling (Rosenberg et al., 2000; FAO, 2009). VMEs and EFHs include spawning, nursery and feeding grounds, together with foundation species (Dayton, 1972), i.e., "a single species that defines much of the structure of a community by creating locally stable conditions for other species, and by modulating and stabilizing fundamental ecosystem processes." This is the role played for examples, by the animal forests, in particular anthozoans (Cerrano et al., 2010; Valisano et al., 2016) whose functional and structural role is receiving increasing attention (Rossi et al., 2017). Numerous initiatives have been developed in order to map the presence and distribution of VMEs and EFHs, and to provide useful tools to help managers and decision makers in the selection of priority areas and in the definition of management plans to ensure the long-term conservation and sustainable use of marine resources (Stecf, 2006; OSPAR Commission, 2010; Rogers and Gianni, 2010; Rengstorf et al., 2013).

Unfortunately, the lack of historical information limits our ability to reconstruct habitat distribution and trends, and assess the current status of VMEs and EFHs. Most of the studies of changes through time have focused on decline of exploited fish populations or top predators (Barausse et al., 2011; Ferretti et al., 2013; Mazzoldi et al., 2014). More limited historical information is available for non-target species, such as benthic invertebrates caught as bycatch. Thus, reconstructing past distribution and abundances of benthic habitats and species is challenging. Such baselines and trends, however, are critical for assessing the current status of EFHs and VMEs and establishing reference targets for their recovery (Engelhard et al., 2016). Over the last decades, "Local Ecological Knowledge" (LEK) has emerged as an alternative approach to collecting information on species presence or abundances when historical data are lacking (Huntington, 2000; Anadón et al., 2009). However, up to now, the use of LEK in the Mediterranean Sea has been limited to collecting information and describing trends in fish diversity and abundances (Azzurro et al., 2011), and discarding of commercially important fish species in the bottom trawl fishery (Damalas et al., 2015a,b). Here, we apply LEK to examine the temporal change of habitat-forming invertebrates in the Adriatic Sea.

The Adriatic Sea is one of the most productive regions of the Mediterranean Sea, hosting a variety of endemic species, and important nursery, spawning, and foraging grounds (Coll et al., 2010; de Juan and Lleonart, 2010; Colloca et al., 2015). Humans have exploited the Adriatic Sea since the prehistoric era (Lotze et al., 2011). This long history of human use, together with global environmental changes (Conversi et al., 2010; Zenetos et al., 2011; Giani et al., 2012) have greatly altered the Adriatic marine environment and ecosystems (Coll et al., 2007, 2009, 2010; Lotze et al., 2011), and ranked the basin as one of the most threatened regions of the Mediterranean Sea (Micheli et al., 2013b). The description and distribution of Adriatic benthic communities have been studied from ancient time both, on a larger scale (Vatova, 1949; Gamulin-Brida, 1974) and a local scale (Paolucci, 1923; Scaccini, 1967; Scaccini and Piccinetti, 1969; Fedra et al., 1976; Crema et al., 1991) with an exhaustive description of its biocoenosis and biodiversity of megabenthic species. Several studies, most of which conducted in the northern Adriatic Sea, have described negative trends and chronic effects of commercial species and benthic communities due to trawling activities (Hall-Spencer et al., 1999; Jukic-Peladic et al., 2001; Pranovi et al., 2001, 2005; Morello et al., 2005; Romanelli et al., 2009). More than 90% of Adriatic marine resources are depleted and the current management of fisheries is inadequate (Lotze et al., 2011; Fouzai et al., 2012). Mean discard rate in Adriatic bottom trawl fisheries ranges between 20 and 67% of total catches, higher than the Mediterranean average (Tsagarakis et al., 2013; FAO, 2016), with a rate that varies according to fishing intensity.

Little is known about temporal variation in the abundance of megabenthic species, foundation species, VMEs and EFHs in the Adriatic Sea. In the northern Adriatic, studies have revealed a shift from benthic communities characterized by the presence of filter-feeding epifaunal organisms forming complex 3D habitat (such as sponges, sea pens, ascidians, holothurians, and large bryozoans) to a community dominated by infaunal and scavengers species (Raicevich et al., 2004; Lotze et al., 2011). This information is not available for other Adriatic sectors. In this study, we used LEK to describe changes in the abundance of habitat-forming megabenthos, and highlight species and ecosystem at risk.

MATERIALS AND METHODS

Study Area

The study was conducted from January to April 2016, in the main fishing ports of the Marche region (Italy, central Adriatic Sea): Ancona, Civitanova Marche, and San Benedetto del Tronto (**Figure 1A**). The area is characterized by sandy-muddy bottoms (Brambati et al., 1983; Spagnoli et al., 2014) with depths that do not exceed 100 m, apart from the Pomo pit (Russo and Artegiani, 1996). Benthic assemblages on the western side and offshore are dominated by endofauna, where the main variety, richness, and biomass is represented by bivalve mollusks, and polychaetes (Vatova, 1949; Gamulin-Brida, 1974; McKinney, 2007). Epifauna biomass is higher in areas around 50–75 m depth, and the most representative organisms include sponges, ascidians, and anemones (Scaccini, 1967; Piccinetti, 1976; McKinney, 2007).

Fishing is intense in the Adriatic region. The main Italian fisheries are small-scale fishing (around 49% of the total number of vessels), followed by dredges (around 26% of vessels), and bottom otter trawl (24% of vessels) (EU fleet register, 2017[1]). In 2011, the Marche region was the third highest region for total volume landings in the Italian Adriatic region, with more than 7,000 tons of total landings in volume coming from bottom trawls. However, landings decreased by 28% between 2004 and 2011 (IREPA Onlus, 2011).

Collection of Local Ecological Knowledge

Information was gathered using a structured interview (Supplementary Materials). In each port, we interviewed only otter trawl fishers, identified through their main associations or cooperatives. These groups included the cooperative "Pescatori Motopescherecci" of Ancona, which includes 54 members (51 vessels are trawlers and 3 vessels are small fishing vessels); the association "Casa del Pescatore" of Civitanova Marche, formed by 34 bottom trawlers; and finally, the fishery located in San Benedetto del Tronto, which includes 35–38 vessels practicing bottom trawling. Fishers were selected on their availability to participate to our survey. An "Oral Consent Procedure" was followed: all potential interviewees were provided with the purpose of the study and with the usage of collected data before obtaining their consent. All involved fishers willingly agreed to participate in the survey. Interviews were kept anonymous and responses were coded with a numeric identifier making it impossible to disclose any personal sensitive data and track the individual fishers.

We selected 18 invertebrate species in five phyla (Porifera, Cnidaria, Bryozoa, Mollusca, and Echinodermata). Species were selected according to one or more of the following criteria: the species should be easily recognizable, common/abundant in the catches, a habitat-forming species, or play a fundamental ecological role (i.e., add tridimensionality to the substrate or acting as a nursery, providing refuge for eggs or small fishes and/or invertebrates; **Table 1**). Among the selected species, only the scallop (*Pecten jacobaeus*) is actively targeted by fishing, while the others are all discarded.

First, we asked questions helping us to characterize the profile of each fisher: age, year he started fishing, and the characteristics of fishing gear used (such as size of the horizontal opening, mesh size of the cod-end nets). Then we used a photographic guide to identify and match local and common species names with the scientific names of the animals for which we were asking questions.

We stratified responses in homogeneous temporal periods and geographic sectors of the study area (**Figure 1A**) to evaluate spatiotemporal changes in the perceived abundance of the focal species. We asked fishers to relate information to four periods: 1980–1989, 1990–1999, 2000–2010, and 2010 up to the present. Once the different species were identified as present in the bycatch for a given period, with the aid of a nautical map (1:750.000) of the Adriatic Sea, we asked the fishers to localize the areas where they usually found each species. The area of interest (minimum latitude and longitude: 42°40′N–12°30′E, maximum latitude and longitude: 44°40′N–15°30′E) was divided into 22 sub-areas. Each sub-area has a size of around 55 × 40 km and was identified by a letter to easily analyze the collected information (**Figure 1A**).

We defined four qualitative classes of reported species abundance, using different metrics (abundance vs. catch volume) for different species depending on the possibility to count single specimens. In particular, for colonial specimens such as cnidarians and bryozoan, we used catch volume metric. Thus, the used qualitative classes of abundance were: 0 = never observed; 1 = rare (1–10 specimens in the cod-end of the net, or for colonial specimens such as cnidarians and bryozoan, "rare" corresponds to an overall dimensions of <¼ of the net in volume); 2 = common (11–50 specimens; for cnidarians and bryozoan ¼–¾ of the cod-end of the net in volume); 3 = very abundant (more than 50 organisms; for cnidarians and bryozoan >¾ of the cod-end of the net in volume). A detected change in abundance class has to be interpreted in relative terms within the species being analyzed but cannot be compared across species. The fishers thus attributed a rank of abundance for each species (0–3), in each time period (1980–1989, 1990–1999, 2000–2010, and 2000–2016), depending on their experience, and fishing location. We asked fishers to identify the abundance of each species for each time period, for each sub-area present on the map. In this manner, the response of each fisher, and the resulting temporal change over time would apply to all single sub-area identified by the fisher.

Statistical Analysis

Statistical analyses were performed using the open access software R (version 3.3.1). All the selected benthic species observed by the fishers as discards in different locations (i.e., identified sub-areas) and in the different time periods were

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[1] Available online at: http://ec.europa.eu/fisheries/fleet/index.cfm

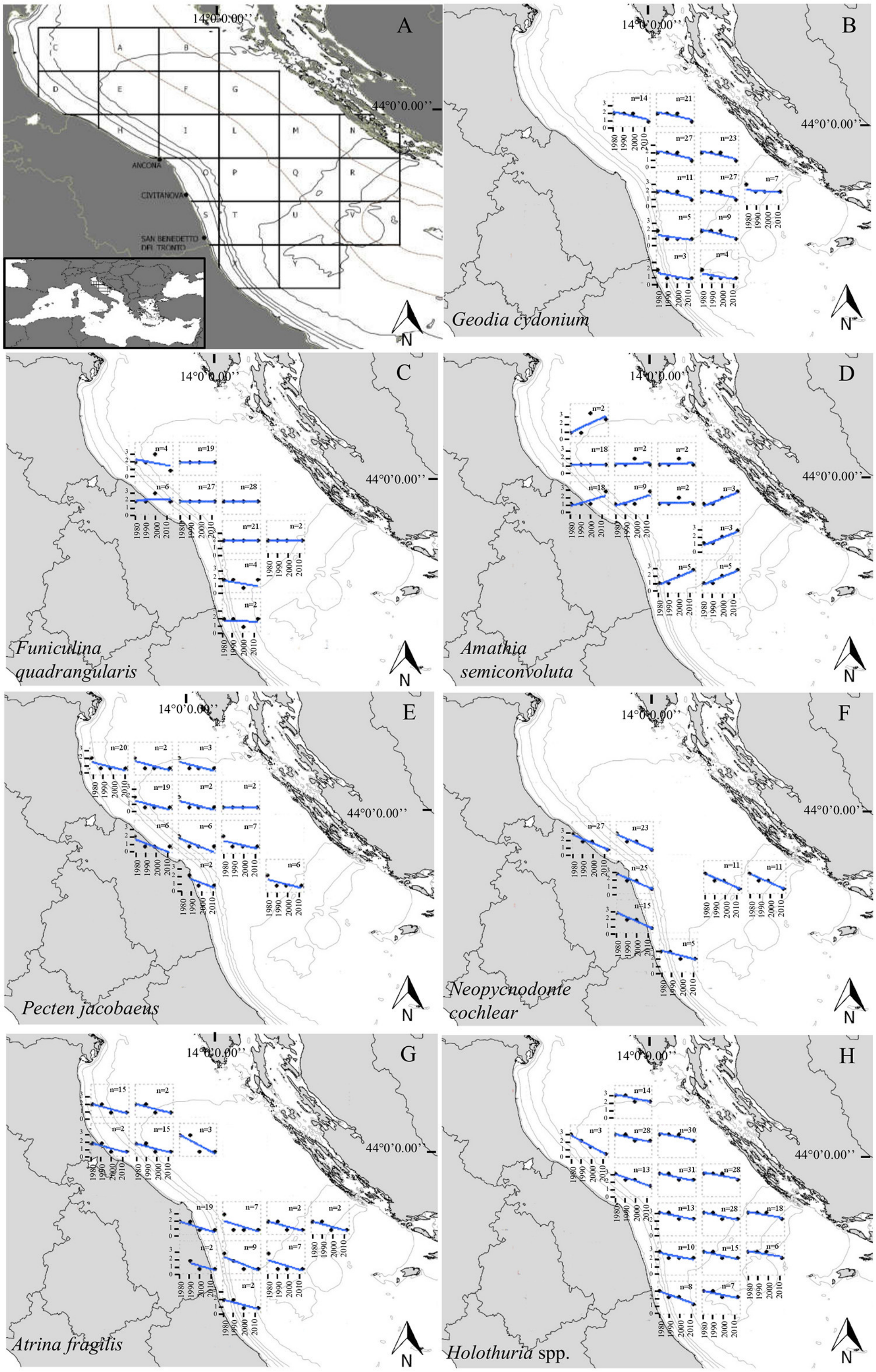

FIGURE 1 | Maps showing the geographical location and ports where fishers were interviewed (Ancona; Civitanova Marche; San Benedetto del Tronto) and trends of the taxa or species analyzed in our study. (A) Grid used to stratify the focal area. Letters are sector codes used to collect information about fishing locations during interviews. Gray lines identify areas outside Italian and Croatian territorial seas; black lines show the bathymetry. **(B)** Trends in the abundance of the sponge *Geodia cydonium*; **(C)** Trends in the abundance of the sea-pen *Funiculina quadrangularis*; **(D)** Trends in the abundance of the bryozoan *Amathia semiconvoluta*; **(E)** Trends in the abundance of the scallop *Pecten jacobaeus*; **(F)** Trends in the abundance of the fan mussel *Atrina fragilis*; **(G)** Trends in the *(Continued)*

FIGURE 1 | Continued
abundance of the deepsea oyster *Neopycnodonte cochlear*; **(H)** Trends in the abundance of *Holothuria* spp. Dots are the class predictions according to the ordinal regression models. The trend lines (blue lines) were included for visual purposes to aid the detection of overall temporal trends in the abundance classes. Even if some sector specific panel is falling on land, it is intended that the relative data has been collected in the portion of the square on the sea. n, number of fishers that gave information per species per sub-area.

TABLE 1 | List of the selected megabenthic species for which we asked fishers to provide qualitative abundances in the central Adriatic Sea, with the ecological, and functional role played by each species and their conservation status.

Phylum	Species name	Ecological role	Conservation
Porifera	*Geodia cydonium* (Linnaeus, 1767)	Nursery, Secondary substratum, Substrate stabilization, Benthic-pelagic coupling, Nutrient cycling	Barcelona Convention 1992[b]
Porifera	*Suberites domuncula* (Olivi, 1792)	Secondary substratum, Benthic-pelagic coupling, Nutrient cycling	Not applicable
Cnidaria	*Lytocarpia myriophyllum* (Linnaeus, 1758)	Nursery, Ecosystem engineer	Listed as priority species in Ireland and Great Britain; no protection in Italy
Cnidaria	*Funiculina quadrangularis* (Pallas, 1766)	Ecosystem engineer, Potential nursery	Critically endangered IUCN red list, 2014[c]
Cnidaria	*Pteroeides spinosum* (Ellis, 1764)	Ecosystem engineer, Potential nursery	Data deficient IUCN red list, 2014[c]
Cnidaria	*Virgularia mirabilis*	Ecosystem engineer, Potential nursery	Vulnerable IUCN red list, 2014[c]
Cnidaria	*Pennatula* spp.	Ecosystem engineer, Potential nursery	Data deficient IUCN red list, 2014[c]
Cnidaria	*Lophelia pertusa* (Linnaeus, 1758)	Ecosystem engineer, Nursery	Barcelona Convention 1992-Annex II[a], Critically endangered IUCN red list, 2014[c]
Cnidaria	*Madrepora oculata* (Linnaeus, 1758)	Ecosystem engineer, Nursery	Critically endangered IUCN red list, 2014[c]
Cnidaria	*Dendrophyllia cornigera* (Lamarck, 1816)	Ecosystem engineer	Vulnerable IUCN red list, 2014[c]
Cnidaria	*Caryophyllia* (*Caryophyllia*) *smithii* (Stokes and Broderip, 1828)	Macrofauna producing consistent skeletons	Not applicable
Cnidaria	*Leptogorgia sarmentosa* (Esper, 1789)	Ecosystem engineer, Nursery	Least concern IUCN red list, 2014[c]
Bryozoa	*Amathia semiconvoluta* (Lamouroux, 1824)	Potential nursery	Not applicable
Mollusca	*Pinna nobilis* (Linnaeus, 1758)	Nursery, Secondary substratum	Habitat Directive 92/43/CEE[a], Barcellona Convention 1992[2b]
Mollusca	*Neopycnodonte cochlear* (Poli, 1795)	Secondary substratum	Not applicable
Mollusca	*Pecten jacobeus* (Linnaeus, 1758)	Food for others animals	Not applicable
Mollusca	*Atrina fragilis* (Pennant, 1777)	Nursery, Secondary substratum	Not applicable
Echinodermata	*Holothuria* spp.	Bioturbation, Remineralization	*Holothuria atra* least concern IUCN red list, 2013[c]

[a] *Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:31992L0043&from=IT.*

[b] *Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean http://195.97.36.231/dbases/webdocs/BCP/bc95_Eng_p.pdf.*

[c] *http://www.iucnredlist.org.*

reported in the respective class of abundance. In particular, each row of the final dataset reported the anonymous identifier of the fisher, the age, the port of origin, the species name, the taxonomic group (phylum) it belonged to, the class of abundance (from 0 to 3), the spatial location (latitude and longitude of the centroid of each sub-area), the distance of each sub-area from the coast, the mean depth of each sub-area, and the time period. When fishers could not determine whether a species was present in the catch, the location in the map or its abundance because they did not remember, NA was entered in the dataset. Only species observed more than twice, for each fishers-sub-areas combination (filter observation for $n > 2$), and for which we had more than half of fishers' answers, were included in the analyses (**Table 2**).

We performed an ordered logistic regression, using the *clmm2* function from the ordinal package, in order to assess the temporal changes of the different species. An ordered logistic regression model is a multinomial regression model where the dependent variable has more than two nominal ordered response categories. In particular, we fitted the cumulative link mixed model

$$\begin{aligned}\text{logit}(P(Yi \le j)) &= \theta j - \beta_1(\text{time}_i) - \beta_2(\text{latitude}_i)\\ &\quad - \beta_3(\text{longitude}_i) - \beta_4(\text{distance}_i)\\ &\quad - \beta_4(\text{depth}_i) - u(\text{fisher}_i)\\ i &= 1, \ldots, n, j = 1, \ldots, J - 1\end{aligned}$$

where $P(Yi \le j)$ is the cumulative probability of the i^{th} observation falling in the j^{th} category or below. Because perceptions about the abundances of the species in the bycatch are expected to vary across fishers, we included fishers as a random effect.

TABLE 2 | Percentages of fishers that clearly remembered (including geographical localization) the selected megabenthic invertebrate species in their by catch and for which we collected clear answers to our questions.

Phylum	Latin species name	% of fishers' answers by species
Porifera	*Suberites domuncola*	42
	Geodia cydonium	84
Cnidaria	*Madrepora oculata*	2
	Caryophyllia (Caryophyllia) smithii	7
	Virgularia mirabilis	9
	Leptogorgia sarmentosa	12
	Dendrophyllia cornigera	19
	Lophelia pertusa	33
	Pennatula spp.	39
	Pteroeides spinosum	42
	Lytocarpia myriophyllum	49
	Funiculina quadrangularis	74
Bryozoa	*Amathia semiconvoluta*	65
Mollusca	*Pinna nobilis*	12
	Pecten jacobaues	77
	Neopycnodonte cochlear	84
	Atrina fragilis	98
Echinodermata	*Holothuria* spp.	100

In our study, the response ordered categories were the classes of abundance (with four levels, each one representing a different qualitative class of abundance), while time, spatial location (latitude and longitude), depth and distance of each subarea from the coastline were the explanatory variables. Ordinal regression enabled us to determine which of our independent variables (if any) had a statistically significant effect on the cumulative probabilities of 4 abundance classes (Christensen, 2015). In particular, we tested the influence of time, of spatial location, of depth, and the relative distance from the coasts (i.e., where we hypothesized a higher fisheries impact on coastal benthic communities), on the abundances of Adriatic megabenthos groups. To avoid collinearity, we first tested the correlation among the available explanatory variables. Then, we calculate the variance inflation factor (VIF). In our case, depth was strongly related to longitude (correlation coefficient > 0.9), which in turn, was an important covariate to account for spatial correlation among observations. Therefore, in interpreting the results of the models, we took longitude as a proxy of depth. Also, latitude and longitude was strongly correlated (VIF ≥ 2), and to include these variables in the models, we followed a sequential regression method (Graham, 2003), which linearly regresses explanatory variables (latitude and longitude) against each other and uses the residuals to represent them. Finally, we also wanted to test whether the perceived temporal change of species abundance varied with distance from the coast. We predicted that as fishers operated farther from the coast, we would have expected a lower rate of change over time. This is because more distant sectors would have been exposed to a lower cumulative amount of effort than closer-to-coast areas. We tested this aspect by including an interaction between distance and time in our initial models. Thus, the final equation of our model was:

$$\begin{aligned}\text{Model} <- \ & \text{clmm2(classofabundance} \sim \text{longitude}_\text{i} \\ + \ & \text{res(latitude}_\text{i} \sim \text{longitude}_\text{i}) + \text{distance}_\text{i} \\ + \ & \text{time}_\text{i} + \text{time}_\text{i} : \text{distance}_{\text{i},} \text{ random} \\ = \ & \text{fisher}_\text{i}, \text{data} = \text{data})\end{aligned}$$

We fitted the mixed effects model by maximum likelihood estimation through Laplace approximation and the final model was selected following a backward stepwise selection procedure, and selecting the model with the lowest Akaike Information Criterion (AIC). The predicted probabilities for an average fisher's perceptions ($u = 0$) have been calculated by including the data used to fit the model.

Georeferenced plots were produced to visualize areas where temporal changes of the selected megabenthic species have occurred, according to fishers' perceptions. To easily and clearly communicate the temporal abundance trends of the analyzed species, a linear regression line, when the temporal effect was significant, was added to the plot. Some species were excluded from the analyses because of a small number of fishers' answers. In these cases we only mapped them to show their presence in the fishing grounds.

RESULTS

We conducted a total of 44 interviews (to 25 fishers from Ancona, 12 from San Benedetto, and 7 from Civitanova Marche). The age of interviewees ranged from 42 to 82 years, with 80% of them older than 50 (around 64% of fishermen were 50–60 years old; fishermen between 40–50 years and between 60–80 years were 18% of interviewees). Only 20% of fishers gave a detailed description of the otter trawl gears they use, the others only stated they use otter trawl gear.

The results of the ordinal regression mixed models indicate an overall reduction of the analyzed species over time (*p*-values for time ranges from <0.001–0.04; **Figures 1B–G**; **Table 3**). Of all the independent variables used, time was significant for all species (*p*-values <0.001–0.04; **Table 3**), longitude was significant in *P. jacobaeus*, *Neopycnodonte cochlear,* and *Holothuria* spp, (*p*-values <0.001–0.005; **Table 3**). The residuals of the regression between latitude and longitude was significant in *Amathia semiconvoluta* (*p*-values < 0.002; **Table 3**). Distance from the coast was significant in *P. jacobaeus*, *A. semiconvoluta,* and *Holothuria* spp. (*p*-values from <0.001 to 0.33; **Table 3**), while the interaction between time and distance from the coast was significant in *A. semiconvoluta*, *P. jacobaeus,* and *Holothuria* spp. (*p*-values <0.001–0.007; **Table 3**). Moreover, in each model, the random effect was significant (*p*-values always < 0.001) indicating that individual fishers added a non-negligible level of subjectivity in their perception of the changes in abundance of the selected megabenthic species.

Declining abundances were reported for the sponge *Geodia cydonium* (**Figure 1B**), while the abundances of the sea pen *Funiculina quadrangularis* remained relatively stable from the

TABLE 3 | Summary of the parameters of the best ordinal regression models (clmm2 models).

Phylum	Latin species name/taxon	Variable significance			Maximum likelihood estimates of the parameters {θj}				Df
			Estimate	***p*-value**		**Estimate**	**Std. Error**	***z* value**	
Porifera	*Geodia cydonium*	Res(lat∼lon)	1.03	0.09	1|2	−2.04	0.72	−2.81	569
		Time	−3.33	<0.001	2|3	6.29	0.85	7.39	
		Time:dist	0.34	0.07					
Cnidaria	*Funiculina quadrangularis*	Time	−0.21	0.04	1|2	−0.75	0.24	−3.09	410
		Lon	−0.19	0.33	2|3	2.86	0.29	9.72	
Bryozoa	*Amathia semiconvoluta*	Res(lat∼lon)	−2.77	0.002	0|1	−2.64	0.25	−10.40	283
		Dist	0.95	<0.001	1|2	−0.10	0.18	−0.56	
		Time	0.78	<0.001	2|3	1.25	0.20	6.13	
		Time:dist	0.38	0.008					
Mollusca	*Pecten jacobaeus*	Lon	−1.61	0.006	0|1	−17.50	2.95	−5.91	284
		Dist	2.04	<0.001	1|2	7.80	1.51	5.14	
		Time	−9.85	<0.001	2|3	18.86	3.19	5.91	
		Time:dist	1.95	<0.001					
	Atrina fragilis	Res(lat∼lon)	0.51	<0.40	0|1	−10.59	1.25	−8.46	308
		Time	−2.85	<0.001	1|2	0.11	0.66	0.16	
					2|3	4.87	0.81	5.97	
	Neopycnodonte cochlear	Time	−3.79	<0.001	1|2	−3.72	0.89	−4.20	454
		Lon	−0.56	0.003	2|3	3.81	0.89	4.27	
Echinodermata	*Holothuria* spp.	Time	−2.59	<0.001	0|1	−7.91	0.59	−13.36	979
		Lon	0.84	<0.001	1|2	−5.12	0.46	−11.21	
		Dist	1.06	<0.001	2|3	0.64	0.37	1.73	
		Time:dist	0.62	<0.001					

Variable names: lat, latitude; lon, longitude; dist, distance from coast; Df, degree of freedom of each model.

1980s up to now, except for very few sub-areas where the species showed a slight decline (**Figure 1C**). The bryozoan *A. semiconvoluta* is the only species that, based on the fishers' perception, had an increasing trend in the last 40 years (**Figure 1D**). Species belonging to the phylum Mollusca, in particular the scallop *P. jacobaeus*, the fan mussel *Atrina fragilis* and the deepsea oyster *N. cochlear,* have declined from very abundant to rare in the study area from the 1980s to the present time (**Figures 1E–G**). The abundance of the holothurians also shows declining trends, even though *Holothuria* spp. are perceived by fishers as still common in most of the central Adriatic sea-bottoms (**Figure 1H**).

Our results did not reveal significant spatial patterns in the trends of species. These trends were similar throughout the study area and no significant differences were apparent between coastal and offshore areas.

Fishers recognized all the species listed in our survey allowing us to map several of them in the central Adriatic fishing grounds (**Figure 1**; Supplementary Figure 1). In particular, the sponge *G. cydonium* was recognized by 84% of interviewed fishers, the bryozoan *A. semiconvoluta* by 65%, the sea pen *F. quadrangularis* by 74%, the bivalves *P. jacobaeus*, *A. fragilis,* and *N. cochlear* by 77, 98, and 84% respectively, and *Holothuria* spp. were recognized by 100% of the interviewed fishers (**Table 2**; **Figure 1**). The sponge *G. cydonium* was reported mainly in offshore sub-areas (**Figure 1B**). The bryozoan *A. semiconvoluta* has been found in several sub-areas of the central Adriatic, usually as a rare occurrence, but with increasing abundances moving toward offshore sub-areas (**Figure 1D**). *P. jacobaeus* was reported mainly in the northern sectors and in sub-areas no deeper than 70 m, while *A. fragilis* and *N. cochlear* were collected also in deeper sub-areas (**Figures 1E–G**). Holothurians were reported in almost all of the analyzed sea bottoms of the central Adriatic Sea (**Figure 1H**). Although all fishers provided us with answers about the abundances and the geographical location of common invertebrates (such as molluscs bivalves or holothurians), only a fraction of them detected the presence in the bycatch of anthozoan species, which occurrences are less frequent and distribution more patchy in the Adriatic sea-bottoms (**Table 2**; Supplementary Figure 1).

DISCUSSION

The impact of towed gears on benthic communities has been extensively studied in many exploited demersal ecosystems of the world (Dayton et al., 1995; Collie et al., 1997; Jennings and Kaiser, 1998; Hall-Spencer et al., 1999; Thrush and Dayton, 2002). These destructive practices have contributed to the decline of habitat-forming species, VMEs and EFHs worldwide. This study reveals that using fishers' LEK can provide a useful tool to describe long-term trends of both target and non-target species. Other studies have recently demonstrated this methods is useful to detect patterns in exploited Mediterranean fish populations (Fortibuoni et al., 2010; Azzurro et al., 2011). Here we highlighted its utility also for a broader range of bycatch species across different marine taxa, including those important to structure benthic habitats. Species such as sponges, bivalves, and holothurians that historically were reported as common in the soft-bottom communities of the central Adriatic Sea (Scaccini, 1967; Scaccini and Piccinetti, 1969; Gamulin-Brida, 1974) were perceived to decline in the last 40 years, especially in the decade 1980–1990 (this study). In contrast, the bryozoan *A. semiconvoluta* increased its distribution and abundance in some areas during the surveyed period, revealing that fishers can easily detect the increase of megabenthic species, particularly those that may affect fishing activities. Fishing grounds where *A. semiconvoluta* is present in high abundance, in fact, are usually not trawled because colonies of this bryozoan can clog trawl nets' meshes (Grati et al., 2013; Salvalaggio et al., 2014).

Our study reveals that LEK may also provide a reliable and alternative source of information to study the spatial distribution of the benthic invertebrates. Clear spatial patterns in the distribution of the selected species in the Adriatic fishing grounds were apparent. In the Adriatic Sea, *P. jacobaues* lives in sandy bottoms shallower than 70 m (Piccinetti et al., 1986), and this aspect was confirmed in our interviews. Moreover, our analysis showed that *P. jacobaeus* is found by fishers also in southern areas respect those previously described, even if in the same bathymetric range were the bivalves used to live. Higher numbers and biomass of *Holothuria tubulosa* and *Holothuria forskali* were found between 20 and 100 m depth, unevenly distributed (Šimunović, 1997; Šimunović et al., 2000). Our analysis revealed that the presence of *Holothuria* spp. goes from 20 m depth down to the deeper sub-areas of the central Adriatic Sea. Thus, we can suppose that environmental factors, such as depth, may be considered directly related to the distribution of Adriatic benthic invertebrates. LEK was also useful to detect rare and spatial restricted species such as the cnidarians *Madrepora oculata*, and *Lophelia pertusa*, which were only previously recorded in death assemblages in the Pomo/Jabuka Pit (Angeletti et al., 2014; UNEP/MAP-RAC/SPA, 2015). Although a small number of fishers gave us answers in relation to these scleractinan species, probably because a small fraction of the interviewees trawled in the Pomo pit area, our maps overlap with the known species distributions (Supplementary Figure 1).

LEK can be an instrumental management tool to reconstruct historical information, such as changes in fish community structure following commercial exploitation and climatic change, or to detect rare species, and species invasions (Berkes et al., 2000; Drew, 2005; Azzurro et al., 2011). In addition, LEK can be used to describe changes in fishing methods and strategies (Damalas et al., 2015a,b), leading in some cases, to approaches of adaptive and qualitative management strategies of marine resources and ecosystems (Berkes et al., 2000). Here we aimed to demonstrate LEK's utility and potential applications as an information tool to characterize the structural changes and alteration of benthic invertebrate assemblages, often unmonitored in conventional fisheries management. Fishers' perceptions may represent in some cases the only option to reconstruct historical baselines for habitats status and to map potential VMEs. Thus, LEK may represent an additional tool to help driving actions needed to reach the ecological targets of "Good Environmental Status" (GES). In fact, the maintenance of benthic biodiversity, sea-floor integrity, and a good status of benthic ecosystems through the protection and restoration of benthic sensitive species and habitats are among the targets of the 11 descriptors of GES of the European Marine Strategy Framework Directive (MSFD-EU, 2008). Moreover, LEK may contribute to the Habitat Directive (92/43 CEE) through the identification of priority habitats present in the central Adriatic Sea, such as biogenic-carbonate reefs or oyster reefs, representing rich and fragile biotopes affected by the high pressure of destructive fishing (Conti et al., 2002; Beck et al., 2011; Taviani et al., 2015). Thus, LEK could provide important information for defining areas to be protected from trawling, providing maps of hotspots of biodiversity, priority habitats and areas with presence of VMEs and EFHs, promoting the development of an efficient and sustainable management of the Adriatic fishing as aimed by the Common Fisheries Policy (CFP) of the European Union (EU).

Despite the potential of LEK for describing temporal changes and spatial distribution of benthic invertebrate species, some limitations of this approach emerged from our analysis. In particular, for some of the selected species (see **Table 2**) information about their presence in the bycatch is limited. This could be related to the fact that fishers do not pay particular attention to species that are not commercially important, or that these species are not so abundant to be commonly observed, or do not affect fishing activities. The interviewed fishers also trawled different fishing grounds with different bottom characteristics and species associations. Thus, the description and identification of the selected megabenthic species, and the likelihood they are observed by fishers, could be related to the natural distribution of the benthic species and to the characteristics of the Adriatic fishing grounds. Moreover, the difference in the number of fishers' responses for the sub-areas identified in our study could be related to the port of origin. In particular, the northern and southern analyzed sectors might be trawled only by a subset of the interviewed fishers, depending on the geographic location of their port of origin. Thus, the number of observations for these sub-areas is smaller compared to the central sub-areas because of their greater distance from the different ports of the Marche region. It was not possible to control for these aspects in this study, but future analyses should address these issues. Finally, our models suggested that there was a significant variability in the response of the individual fishers (random intercept in our model). This aspect needs to be considered when analyzing results from interview surveys to obtain unbiased parameter estimates for other fixed effects. The variability among fisher may be due to a variable perception of abundance among individuals due to experience, recollection ability, and any other factor capable of biasing the index of abundance being modeled (Grant and Berkes, 2007). In the absence of specific information to control for these biasing factors, it is reasonable to assume that each fisher influenced the variability of the responses in a random fashion according to a normal distribution with mean 0 and standard deviation to be estimated from the data.

The widespread perceived decline of benthic species playing important ecological roles (**Table 1**) in the central Adriatic may have altered the Adriatic marine ecosystem functioning over the past decades. Changes in benthic invertebrates we described here are congruent with patterns of decline described by other authors in the northern Adriatic through use of standard sampling methodologies such as dredges and trawl surveys (Scardi et al., 1999; Raicevich et al., 2004). These studies reported a net reduction of the ratio discards/commercial species, with a decline or disappearance of large filter feeding organisms (e.g., the sponge *Geodia*) documented from 1980s to 2000s (Raicevich et al., 2004) together with a general decreasing trend of the diversity of macrobenthic assemblages (Scardi et al., 1999). In other ocean sectors, the declines in benthic invertebrates triggered entire regime shifts (Kaiser et al., 2000; Jackson, 2001) and we expect that similar consequences may have occurred also for the Adriatic Sea. Detecting the occurrence of these ecological changes is of paramount importance for future studies.

Several factors may have driven the declines of megabenthos species living on soft bottoms of the Adriatic basin. Declines of sponges and other benthic invertebrates, for example, has been associated with anoxic events (Fedra et al., 1976) in the northern Adriatic basin. Climate change, such as temperature anomalies, caused mass mortalities events in the central basin (Di Camillo et al., 2013; Di Camillo and Cerrano, 2015; Kružić and Popijač, 2015), and direct and indirect impacts of human activities, such as fishing, have reduced the biodiversity and the complexities of the Adriatic benthic communities (Raicevich et al., 2004; Pronzato and Manconi, 2008; Lotze et al., 2011). While we cannot exclude the influence of multiple factors in driving the decline of megabenthic species described here, our analysis supports the hypothesis that intense trawling in the Adriatic Sea over the past decades may have been a major factor determining the alteration of the Adriatic soft bottom communities. In 1980s, Italian Adriatic regions reached the maximum number of fishing vessels together with the complete development of highly damaging fisheries introduced in the 1960s (Froglia, 2000; AdriaMed, 2004; Romanelli et al., 2009). In the 2000s the total number of fishing vessels decreased (AdriaMed, 2004), however, new technologies such as GPS systems have been introduced, improving the exploitation of new fishing ground (Fortibuoni et al., 2017) and the total fishing pressure on Adriatic seabed bottoms is currently considered unsustainable. Because the LEK data we collected in our study to detect fishers' perceptions is mainly qualitative, our models did not detect clear patterns moving from coastal to offshore areas. However, distance from the coast is one of the most important variables affecting our regression models, for example for *P. jacobaeus*. In particular, our model suggests that at increasing distance from the coast, higher classes of abundance are more likely (**Table 3**). This relation with the proximity to the coastline is characteristic of a community being exploited, such as coastal communities that typically are exposed to a heavier and more prolonged history of exploitation than those offshore. Automatic Identification System and Vessel Monitoring System analysis clearly revealed that trawling fishing effort is higher in coastal areas with respect to offshore areas in the central Adriatic Sea (Santelli et al., 2017). However, chronic and intensive effects of bottom trawling fishing, with habitat degradation are well-known (Pusceddu et al., 2014), and the long-term exploitation of the Adriatic basin could have homogenized and simplified Adriatic soft bottoms habitats and species composition even in offshore areas. In particular, habitats formed by slow growing and long-lived specimens such as sea pens, hydroids, or corals, have a high vulnerability to fishing and even reduced fishing effort may cause considerable damage to these species, preventing their recovery (Troffe et al., 2005; Greathead et al., 2014). Moreover, the impacts of trawl fishing gears on the seabed differ depending on the sediment compositions and on bottom trawl target species (Pranovi et al., 2001, 2005; Eigaard et al., 2016). Gear characteristics (e.g., changes in number, the size of meshes in the cod end net, modification of the design of the doors, and other parts of the trawl net) also possibly affected the level and the type of damage by trawling gear on megabenthos. Our study did not consider different gear types, thus the pattern described by fishers is only relevant to a specific type of fishing gear. All the interviewed fishers were otter trawler and used a fishing gear that is generally standard across our focal area (that is an Italian otter trawl as specified in Fiorentini et al., 1999). However, because the interviewed fishers in most cases did not give us the specific characteristics of their fishing gears (e.g., detailed size of trawl net and numbers of used gears per haul), it was not possible to confirm and clearly relate the fishing effort and fishing gear characteristics with the observed megafauna trends. More detailed analysis and new interviews are needed to fill these gaps and to explore the most adequate restoration measures (Bastari et al., 2016) that need to be urgently adopted.

CONCLUSIONS

Historical studies are fundamental for understanding long-term changes in marine ecosystems. LEK surveys provide an opportunity to fill this knowledge gaps as we demonstrated here by focusing on historical changes of benthic invertebrates species in the exploited Adriatic Sea. These approaches provide an opportunity to reconstruct reference points for benthic communities and may help management in setting recovery target for ecosystem structure and even function at local and regional scale. Therefore, extending these studies on a broader geographic scale is a promising approach for drawing historical baselines and inform marine management.

ETHICS STATEMENT

Ethics approval was not required for this study as per institutional guidelines and Italian law and regulations. In compliance with the aforementioned guidelines, laws and regulations, oral informed consent was obtained from all research participants. All potential interviewees were provided of the purpose of the study and of the usage of collected data before obtaining their consent. Their answers were anonymized and it is not possible to link the statements back to individual subjects.

AUTHOR CONTRIBUTIONS

AB gave substantial contributions to the conception and design of the work, analysis of data, and drafting the work, and final approval of the version to be published. JB gave substantial contributions to the acquisition and analysis of data. FF gave substantial contributions to the work conception, analysis and interpretation of data, and revising the work critically for important intellectual content, and final approval of the version to be published. FM and CC conceive the work and gave substantial contributions to its design, revising the work critically for important intellectual content, and the writing of the article.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fmars.2017.00157/full#supplementary-material

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PERSPECTIVE
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Untying the Mediterranean Gordian Knot: A Twenty First Century Challenge for Fisheries Management

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Management of fisheries in the Mediterranean basin has often been described as a unique and complex challenge, due to their multi-specificity, the diversity of gear-types, and the number of nations involved. This perspective has gone hand-in-hand for decades with a lack of strong political will from decision-makers, who have been unwilling to put Mediterranean fisheries management high on their agendas. Over time, exploitation rates of demersal stocks have increased and in 2016, 97% of shared stocks assessed in the Mediterranean were reported to be overfished. An alarm bell about the chronic overfishing of Mediterranean fish stocks was rung by European policy makers in 2015, exactly 20 years after the Code of Conduct for Responsible Fisheries adopted by the Food and Agriculture Organization mandated that states should ensure the sustainable use of fishery resources. In this perspective, we: (i) review the context of fisheries management in the Mediterranean; (ii) identify the potential factors that may have hindered management and; (iii) discuss how the reformed European Union Common Fisheries Policy and the binding commitments laid down in its text may lead to knock-on effects for fisheries management in the international Mediterranean context, if properly implemented. In this line, we also present the example of demersal fisheries management in the Strait of Sicily, which may represent a starting point for science-based management in the Mediterranean.

Keywords: Mediterranean, overfishing, policy, knock-on effect, Common Fisheries Policy

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THE LONG ROAD TO MANAGEMENT OF SHARED MEDITERRANEAN FISH STOCKS

The need for effective management of shared fisheries resources in the Mediterranean Sea was first highlighted during the aftermath of the Second World War. In 1948, the 4th Session of the FAO Conference agreed to set up an international organization dedicated to Mediterranean fisheries management, which was formalized with the 1952 establishment of the General Fisheries Council for the Mediterranean. This preliminary attempt to manage fisheries in the region was limited in its powers; the measures adopted by the Council were not binding for the Signatory States and it lacked operational activity (OECD, 2005). At time, information on the status of Mediterranean stocks was very limited and mainly relied on FAO statistics, with their limitations of negligible catches reported for many species (STECF, 2015). Periodic updates aimed at assessing the status of demersal and small pelagic Mediterranean resources only began to be carried out from 1970 onwards (FAO, 1999).

When the United Nations Convention on the Law of the Sea (UNCLOS) entered into force in 1994, requiring all members to cooperate in the conservation and management of living marine resources, the General Fisheries Council for the Mediterranean was the oldest Regional Fisheries Management Organization (RFMO) in the world. However, it was still far from acting as such, since its constitutive text lacked a clear mandate and objectives. In parallel, the mid-90s were marked by the adoption of the FAO Code of Conduct for Responsible Fisheries (1995) and the Straddling Fish Stocks and Highly Migratory Species Agreement (UN, 1995), which formally called for the establishment of the RFMOs.

As a consequence of this international process to modernize management of shared stocks, in 1997 the General Fisheries Council for the Mediterranean revised its Agreement and became the General Fisheries Commission for the Mediterranean (GFCM, hereafter). A Scientific Advisory Committee (SAC) was also established, with the task of annually conducting and validating stock assessments. The amended Agreement entered into force in 2004. This change represented the key milestone for fisheries management in the region. In 2005, GFCM was fully empowered as an RFMO responsible for adopting binding fisheries management rules for transboundary fish stocks.

Nowadays, GFCM has under its purview the management of shared demersal and small pelagic stocks, which for management purposes are divided into 30 geographical sub-areas (GSAs) in the Mediterranean and Black Seas. It is composed of 24 Members (23 member countries and the European Union) and three Cooperating non-Contracting Parties (i.e., Bosnia and Herzegovina, Georgia and Ukraine).

The EU as well as Bulgaria, Croatia, Cyprus, France, Greece; Italy, Malta, Romania, Slovenia and Spain are Contracting Parties to the Agreement establishing GFCM. Pursuant to Article 218(9) of the Treaty on the Functioning of the European Union, the Council of the EU authorizes the European Commission (EC) to negotiate on behalf of the EU in RFMOs when they are called upon to adopt acts with legal effect on matters falling within the EU's competence. Within GFCM, the EU is the main fishing actor in terms of landings, number of vessels and fleet capacity, with Italy accounting for the greatest fleet capacity among EU Member States (MS), and the second-largest capacity among all the Mediterranean riparian states, after Turkey (**Table 1**).

THE MEDITERRANEAN FISHERIES "GORDIAN KNOT"

In the Mediterranean, fisheries exploitation has reached high levels coupled with low levels of selectivity (Colloca et al., 2013; Vasilakopoulos et al., 2014; Tserpes et al., 2016). Studies aimed at investigating the trends in Mediterranean stocks have shown that exploitation rates have increased over time for a considerable number of small pelagic and demersal fish stocks (Vasilakopoulos et al., 2014; Tsikliras et al., 2015), combined with an increasing proportion of juveniles in catches (Vasilakopoulos et al., 2014). By 2016, 97% of shared stocks assessed were reported to be overfished (FAO, 2016a). Despite this, scientific advice has rarely been followed for implementing management (Lleonart and Maynou, 2003; Cardinale and Scarcella, 2017).

Mediterranean fisheries have historically been regulated by input measures in the way of effort regulation, generally accompanied by methods of indirect effort control, such as various technical measures (Colloca et al., 2013; Vasilakopoulos et al., 2014; Damalas, 2015). However, even if effort control systems are properly implemented, it often results in fishing mortality being higher than intended (Stefansson and Rosenberg, 2005), as has been the case for the Mediterranean (Cardinale and Scarcella, 2017). Consequently, management based on technical measures has failed to ensure the long-term sustainability of fisheries and the conservation of sensitive habitats (Tudela, 2004; Colloca et al., 2013). This, alongside with poor or non-existent enforcement of fisheries management measures, has led to a point of no return in the mismanagement and decline of Mediterranean stocks, which is likely to continue if no remedial action is taken (Vasilakopoulos et al., 2014).

This situation has generated a "Gordian knot" in Mediterranean fisheries management, both within the EU (Section a) and GFCM (Section b), that represents a paramount challenge for managers in terms of urgently finding appropriate solutions for reversing decades of overfishing.

(A) THE EUROPEAN MEDITERRANEAN FISHERIES MANAGEMENT CONTEXT (1994–2014)

Initial interventions to regulate the EU fleet started in the early 90s, administered by the EC, and aimed at restructuring the EU's fishing fleets by fixing ceilings on fishing capacity by fleet segments (OECD, 2005). These limits apparently reduced the size of the Mediterranean EU fleet, and the limits they set on total tonnage and engine power remained in force. However, fleet modernization schemes, strongly subsidized under the Funding Instrument for Fisheries Guidance and other funding mechanisms, created a technological creep that has perpetuated an unbalance between fishing capacity and efficiency and fish availability that still persists today. For example, in the Balearic Islands (Spain), a reduction in fishing vessels (from 70 in 1977 to 30 in 2009) corresponded to a much steeper increase in average Horse Power (HP) per vessel (from 15 HP in 1977 to 600 HP in 2009) (Quetglas et al., 2013). This perverse development has not only failed to reduce fishing mortality on stocks, but has also constituted a useless expenditure of substantial amounts of public funding initially allocated to solve the problem. In 2009, total subsidies to the European fishing sector were equivalent to 50 percent of the value of total fish catches by the EU in that same year (€6.6 billion; Schroeer et al., 2011).

The first regulation establishing measures for the conservation of fishery resources in EU Mediterranean waters was adopted by the European Council in 1994 (Council Regulation (EC) No 1626/94), a full 10 years after the entry into force of the first Common Fisheries Policy (CFP; 1983) and fisheries management plans for the North East Atlantic. The aim of this Regulation was to lay down a first set of technical measures that would apply

TABLE 1 | Summary of reported landings, vessels, and fleet capacity of GFCM contracting parties, cooperating non-contracting parties, non-contracting parties, or relevant non-State actors in the Mediterranean and Black Seas.

	Landings		Vessels		Fleet capacity (GT)	% of total
	Average landing (tons)	% of total	Number of vessels	% of total		
EU:	524,578	**35.60**	43,005	**46.37**	380,498	**33.14**
Italy	249,500	16.93	12,469	13.45	163,994	14.28
Spain	108,100	7.34	2,663	2.87	56,607	4.93
Greece	81,900	5.56	15,688	16.92	74,811	6.52
Croatia	42,100	2.86	7,733	8.34	53,380	4.65
France	29,900	2.03	1,461	1.58	15,777	1.37
Bulgaria	7,715	0.52	704	0.76	3,743	0.33
Cyprus	1,749	0.12	943	1.02	3,388	0.30
Malta	1,419	0.10	1,015	1.09	7,020	0.61
Romania	1,258	0.09	159	0.17	790	0.07
Slovenia	937	0.06	168	0.18	597	0.05
Portugal	–	0.00	2	0.00	391	0.03
Non-EU:						
Turkey	459,400	31.18	16,447	17.74	175,328	15.27
Algeria	115,400	7.83	4,778	5.15	69,711	6.07
Tunisia	101,400	6.88	13,826	14.91	114,030	9.93
Ukraine	68,900	4.68	135	0.15	N/A	–
Egypt	67,300	4.57	2,988	3.22	72,336	6.30
Libya	41,700	2.83	4,641	5.00	164,928	14.36
Morocco	35,600	2.42	2,146	2.31	15,354	1.34
Russian Federation	32,000	2.17	33	0.04	N/A	–
Georgia	12,600	0.86	47	0.05	N/A	
Lebanon	3,574	0.24	2,623	2.83	6,474	0.56
Albania	2,801	0.19	511	0.55	10,768	0.94
Syrian Arab Republic	2,768	0.19	31	0.03	2,462	0.21
Israel	2,643	0.18	400	0.43	N/A	–
Palestinian Territories	2,118	0.14	759	0.82	N/A	–
Montenegro	645	0.04	135	0.15	1,309	0.11
Monaco	2	0.00	N/A			0.00
Japan	–	0,00	229	0.25	134,982	11.76

Data for EU have been aggregated (aggregated % in bold). Modified from FAO (2016b).

equally to all MS fishing in the region. Unfortunately, despite the fact that fisheries in the Mediterranean were already much more weakly regulated that in the North-East Atlantic, Regulation 1626/94 set a weaker double-standard by being adapted to "*the particular circumstances*" of Mediterranean fisheries.

With the reform of the CFP in 2002 (Council Regulation (EC) 2371/2002), the ecosystem approach to fisheries management was endorsed and adopted, along with the objective of achieving the sustainable long-term management of EU fish stocks. However, in the same year, the EC continued to promote a double standard in fisheries management. It presented its Action Plan for Mediterranean fisheries (EC, 2002) to deal with "*specific features of the Mediterranean*" where "*the CFP does not apply in the same way as elsewhere in the Union*" though "*all species of fish are subject to overexploitation*" (EC, 2002). In the following years, MS set effort controls, adopted mostly at the country level, and on the basis of fleet logistics in their exploitation dynamics of multiple stocks, without taking into account the geographical distribution of stocks and the fisheries exploiting them (Cardinale and Scarcella, 2017).

In 2006, that regulation was then replaced by Council Regulation (EC) No 1967/2006—commonly referred to as the MedReg—which included a series of technical measures to regulate fisheries in EU Mediterranean waters. The technical measures adopted under the MedReg have often been inconsistent with scientific evidence; for example, minimum landing sizes for some commercial fishes have been set below sizes at maturity (Mouillot et al., 2011). This lack of science-based measures, coupled with poor implementation levels and enforcement, have been detrimental to stocks (Cardinale and Scarcella, 2017) and have led to poorly selective demersal fisheries whose catches are mainly dominated by juveniles (Colloca et al., 2013; Vasilakopoulos et al., 2014; Cardinale and Scarcella, 2017).

The MedReg also introduced the requirement for MS to adopt National Management Plans (NMPs; Art. 19) for certain fisheries in their territorial waters. Most of the current 34 NMPs were established years after the 2010 deadline (EC, 2016) while, not surprisingly, monitoring and assessment of their effects on stocks has been very limited.

In December 2013, a reformed CFP entered into force (EU Regulation No 1380/2013), changing the existing fisheries management landscape entirely. Critically, it requires population of fish stocks to be restored and maintained above biomass levels capable of producing maximum sustainable yield (MSY) by 2015, or by 2020 at the very latest. It requires the precautionary and ecosystem-based approach to fisheries management to be implemented so as to ensure that negative impacts on the marine ecosystem are minimized. It also mandates a gradual implementation of a landing obligation and ban on discards, by avoiding and reducing unwanted catches. The 2013 CFP also laid out a new approach for the EU within RFMOs (see below).

The key tool for restoring and sustainably managing fish stocks under the CFP is intended to be the implementation of multiannual management plans (MAPs). However, nearly four years after the adoption of the CFP, no such plans have yet been established in EU Mediterranean waters.

(B) THE GFCM FISHERIES MANAGEMENT CONTEXT (2003–2016)

In 2003, the Declaration of the Ministerial Conference for the Sustainable Development of Fisheries in the Mediterranean empowered the SAC to advance GFCM fisheries management based on sound scientific advice. Since 2005, a set of binding measures have been adopted in GFCM, although these mainly have been input control measures, and the majority have been poorly or not implemented at all.

One example arose following repeated advice from SAC (from 2001-2004) to reduce fishing mortality and limit the capture of juveniles, as a measure to address overexploitation. In 2005, GFCM adopted a Recommendation for the immediate implementation of a minimum 40 mm mesh size for the entire cod-end of demersal trawls (GFCM, 2005). However, only 2 years later, this measure was derogated, allowing cod-end mesh sizes smaller than 40 mm to operate until 2010 (GFCM, 2007). In 2009, the 40 mm minimum mesh size was adopted for the entire region (GFCM, 2009), but only from 2012 onwards: a delay of over seven years after the SAC advice. Still today, there are concerns that the 40 mm mesh size is far from being implemented in the region and its implementation may not be properly monitored.

Close to its 60th anniversary, GFCM launched a process to modernize its legal and institutional framework, following an external performance review in 2009–2011 (GFCM, 2011) which, *inter alia*, advised GFCM to revise its Agreement so as to align it with the principle of sustainable management laid down in the FAO Code of Conduct for Sustainable Fisheries. This modernization process—in which civil society also took part (Oceana, 2012)—concluded in 2014. The resulting fourth amendment to the GFCM Constitutive Agreement finally included the obligation to halt overfishing so as to achieve MSY, through the adoption of MAPs based on the ecosystem-based approach to fisheries management and the implementation of the precautionary principle.

KNOCK-ON EFFECTS

The 2013 CFP identifies clear management objectives, along with a timeline for meeting them. It also defines the framework within which the EU must operate in RFMOs. In particular, Article 29 establishes that the EU position must be based on the best available scientific advice, so as to ensure that the precautionary approach is applied, and that fish stocks are managed above levels which can produce MSY, while ensuring the profitability of the fishery, in line with Articles 2.2 and 2.5c of the CFP. Furthermore, the EU has the legal obligation to "*seek to lead the process of strengthening the performance of RFMOs so as to better enable them to conserve and manage marine living resources under their purview*."

This new EU approach to RFMOs entered into force while the process to amend the GFCM Agreement was ongoing. The EU was the leading voice in the process, promoting and contributing to the Task Force working directly on the amendment of the Agreement. Indeed, the 2013 CFP obliged the EU to ensure that both the precautionary approach and ecosystem-based management would be reflected and embedded in the GFCM. The final GFCM text was strongly influenced by the 2013 CFP, which is believed to have produced a knock-on effect on the reform of GFCM.

The synergy of the two revised regulations, the 2013 CFP and the 2014 GFCM Agreement, together hold the potential to drive the reshaping of fisheries management in the Mediterranean. Furthermore, the focus on multiannual management plans that include clear objectives, and are supported by effective control and enforcement, has been indicated as the alternative management approach that could reverse the decline of Mediterranean stocks (Vasilakopoulos et al., 2014; Cardinale and Scarcella, 2017). The Mediterranean fisheries crisis has been building for decades: the new regulatory tools provide hope and a sound basis for rebuilding fish stocks to levels that can produce MSY.

DEMERSAL FISHERIES IN THE STRAIT OF SICILY, A POTENTIAL TURNING POINT FOR SCIENCE-BASED MANAGEMENT

The first case in which the 2013 CFP and the 2014 GFCM Agreement have both been applied was the establishment of a MAP for the fisheries targeting deep-water rose shrimp (*Parapenaeus longirostris*) and, secondarily, European hake (*Merluccius merluccius*) in the Strait of Sicily (GSA 12 to 16). These fisheries are carried out by bottom trawlers from Italy, Malta and Tunisia.

Fishing mortality for hake and deep-water rose shrimp has been estimated at 4.5 and 1.2 times, respectively, above sustainable levels (FAO-GFCM, 2015). Since 2006, GFCM prioritized hake in GSA 12–16 on its agenda due to the high level of overfishing and catches of juveniles (GFCM, 2006). Since then, however, no management had been put in force. Finally, in 2014, following the adoption of the 2014 GFCM Agreement, the EU tabled a proposal to address the overfishing of key demersal stocks in the Strait of Sicily. While this proposal was not adopted at the time, the SAC was requested to provide comprehensive advice in the context of a multiannual management plan (FAO-GFCM, 2014). To achieve and sustainably manage key commercial stocks of hake and deep-water rose shrimp (F_{MSY}), the SAC advised a reduction of fishing mortality by 20% for deep-water rose shrimp and 70% for hake, to be progressively achieved by 2020 through the adoption of a MAP, which also included three Fisheries Restricted Areas to be closed to bottom trawling to reduce fishing mortality of juvenile hake (SAC-SRC-CM, 2016). This scientific recommendation allowed the EU to table a proposal at the 40th GFCM Commission, which was then adopted with consensus in May 2016 (GFCM, 2016).

Compared to other management strategies in place until now in the Mediterranean, this newly adopted MAP represented a significant advance, in that it includes the explicit objective of recovering stocks to MSY, in line with both the 2013 CFP and 2014 GFCM Agreement, and specifically by 2020, in line with the CFP obligation. This consistency with the CFP was especially important, considering that the EU fleet has the highest stake in this fishery, with 82% of all vessels involved in the fishery flying EU flags (Gancitano et al., 2016).

LESSON LEARNED TO MAKE A CONCRETE CHANGE IN THE MEDITERRANEAN FISHERIES MANAGEMENT

In conclusion, despite the fact that policy tools were already in place during the past two decades (i.e., UNCLOS, FAO Code of Conduct, 2002 CFP) and already provided a framework to halt overfishing, they have been disregarded in the Mediterranean due to lack of implementation and enforcement. In particular, EU fisheries management in the region has been characterized by weak institutional structures and poor levels of compliance (Smith and Garcia, 2014; Vasilakopoulos et al., 2014). Under the MedRed, MS have failed to take responsibility for properly translating the regulation into management, and EU Mediterranean fisheries management has proven ineffective for achieving the objectives of the former 2002 CFP of sustainably managing fish stocks.

The current complexity of the situation gives only two options: untie the Gordian knot with a strong commitment from all parties involved, and on the basis of scientific advice; or cut it, jeopardizing Mediterranean stocks forever. Here we consider the following:

(i) Input control measures have historically been considered the palliative cure to deal with Mediterranean fisheries. However, that approach, combined with weak control and enforcement, has contributed to fostering overfishing over decades. Output control rules should be the basis of new multiannual management plans, together with measures aimed at reducing unwanted catches and implementing ecosystem-based management.

(ii) The MAP for demersal shared stocks in the Strait of Sicily has represented a tipping point in Mediterranean fisheries management. Clearly this development in science-based management has been influenced by the principles and obligations of the 2013 CFP on EU fisheries management priorities, as well by the reshaped objectives and approach of GFCM. However, this approach is still in its embryonic phase and needs to be proven and tested by real commitment from the parties involved. Either the plan is properly implemented, or if not, it would then represent yet another failure for Mediterranean fisheries management—and possibly the ultimate one.

(iii) Based on the dynamics of fisheries policy and implementation over the last two decades in the region, it is clear that legislation will not deliver the desired results if implementation and enforcement are not placed equally high on the policy agenda. To achieve the maximum benefit of the synergies between the 2013 CFP and 2014 GFCM Agreement for driving the recovery of Mediterranean fish stocks, it is therefore critical that both policy tools must be urgently and fully implemented and enforced. This responsibility rests directly on the EU MS and other Mediterranean countries, in the interests of their fishing futures.

AUTHOR CONTRIBUTIONS

IV, AP, and MC contributed to the conceptualization, writing of the original draft, and revision of the paper.

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The Saga of the Management of Fisheries in the Adriatic Sea: History, Flaws, Difficulties, and Successes toward the Application of the Common Fisheries Policy in the Mediterranean

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In the past 40 years, the fishery in the Mediterranean Sea has seen numerous changes in technology, fleet composition, effort allocation, and management strategies. In this paper, our aim is to summarize the improvements, and highlight the flaws and difficulties that have characterized fisheries management in the Mediterranean Sea in the past decades. We (the authors) advocate the importance of the regionalization of the Common Fisheries Policy (CFP) in the Mediterranean. We focussed on the Adriatic Sea, with two case studies—the fishery for sardine and anchovy, and the fishery for Nephrops. The former is emblematic as it is one of the most valuable and well-studied fisheries in the Mediterranean but it is also an example of a management process that is slowly bearing fruit. Nephrops, on the other hand, has been facing the same destiny as other stocks in the Mediterranean; namely, its peculiar biology, a complex fishery, a poorly tailored data collection and inadequate assessments, have delayed action until very recent times. We use these examples to cover several aspects of Mediterranean fisheries management: (i) a historical overview of the development of these fisheries and their management; (ii) an overview of the main players involved in the scientific analysis and management process and their current and ideal roles; (iii) the flaws of the current stock assessment system; and (iv) recent developments and potential solutions to comply with the latest reform of the CFP before 2020. We argue that to align Mediterranean management with the CFP and achieve MSY targets, the lack of coordination and definition of roles between the General Fisheries Commission for the Mediterranean, the European Commission Directorate-General for Maritime Affairs and Fisheries, the Scientific, Technical and Economic Committee for Fisheries and the Joint Research Centre need to be resolved. There is a need for adequate assessment models and data to answer increasingly complex management questions, as well as regular external review of the stock assessment models to assure their quality. Finally, the need for the implementation of a TAC system as an effective tool for Mediterranean fisheries to achieve sustainability is discussed and advocated.

Keywords: CFP, regionalization, Adriatic Sea, small pelagics, *Nephrops norvegicus*, total allowable catch

INTRODUCTION

The Common Fisheries Policy (CFP) is the instrument used by the European Union to ensure the sustainable exploitation of marine resources exploited by European fishing fleets. After many years of criticisms and failures, in 2014 the CFP underwent substantial reforms which were thoroughly discussed in the so called "Green paper" of the European Commission (EC) (CEC, 2009). The content, in an innovative and modern fashion, tried to address all the problems and faults of previous management identified by policy makers, scientists and stakeholders, ranging from biological and economic aspects, to legal and political features (Payne, 2000; Khalilian et al., 2010; Villasante et al., 2011; Da Rocha et al., 2012).

At the time of its inauguration in 1982, the CFP was, *de-facto,* a regional policy centered on the North Sea. Since then, the area of action has expanded enormously, and the lack of regionalization has been recognized as one of the main flaws of this earlier version of the CFP; however, this issue was never taken into consideration in subsequent reforms. Following repeated expression of the need for regionalization, the reduction of a centralized top-down management system in favor of a decentralization of power to regional bodies became a major aspect of the new reform that took effect in 2014. The idea of regionalization aims to set up broad, common objectives and underlying principles for a sustainable management, whilst possibly implying a transfer of responsibility for detailed management to regional or sub-regional bodies. This important shift, from a central authority in Brussels to multiple organizations, intends to bring decisions closer to those mostly affected and having deeper knowledge and experience on specific fisheries and/or environment (Symes, 2012).

The importance of regionalization is even more striking when comparing the issues faced by Northern Europe with those pertinent to the Mediterranean area (Raakjær, 2011). A different management system, the interaction with non-EU countries, a long history of exploitation and a series of cultural gaps between the two regions increase the risk of making ineffective measures that do not take into account this diversity.

The concept of a regionalized CFP is in theory also supported by the effort devoted to the development of an ecosystem approach to fisheries management: if each ecosystem is to be managed at the right geographical scale, it should be treated as a single eco-region, allowing tailor-made regulations based on an understanding of the dynamics of specific fisheries and eco-systems (Raakjær, 2011).

Another important aspect to be considered is the link that the original CFP shares with the concept of the Total Allowable Catch (TAC): in fact, in the words of Holm and Nielsen (2004), it can be argued that the "TAC Machine and the CFP constituted each other reciprocally." When first established, the negotiation over the CFP focussed on the importance of sharing the fisheries resources among member states following some rules dictated by the new-born methodology know as Virtual Population Analysis (VPA) (Holm and Nielsen, 2004). The TAC philosophy has several advantages, such as a tidy division of labor between science and politics, the routinization of scientific work, and the definition of a clear management objective whose achievement is in theory measurable (Holm and Nielsen, 2004; Hoydal, 2011). Its success is strongly dependent on the implementation of the rule itself at the political level: in the Northerly seas, where most species are subject to quotas, failures occurred due to final regulations from EU advising for much higher catches than what scientists advised (Cardinale and Svedäng, 2008; Villasante et al., 2011). TAC has never really taken over in the Mediterranean area, where such output control might be complicated by the mixed fisheries context: here the fishery is mostly regulated through the control of fishing effort and fishing capacity, specific technical measures, minimum conservation reference size, and closures of areas and seasons for fishing; these measures however haven't proven to be successful either and substantial actions are now required (Cardinale and Scarcella, 2017).

Despite the initial idea behind the reform of the CFP, the constraints imposed by the competence order established in the Treaty on the Functioning of the European Union (TFEU) do not allow an effective re-ordering to fit a regional scale (see Salomon et al., 2014 for details). Surely, this provision can be a starting point and a prototype model for Member State cooperation, but the lack of an appropriate organization of the bodies involved, together with closure toward the variety of different political, social and legal frameworks and situations around Mediterranean coastal countries, is slowing the process and affecting achievement of the final goal.

In the last decade, several papers have been published to discuss, eviscerate and review the intrinsic problems of the old and new CFP (Daw and Gray, 2005; Frost and Andersen, 2006; Da Rocha et al., 2012; Hegland et al., 2012; Svedäng and Gipperth, 2012; Salomon et al., 2014; Ross, 2015; Soma et al., 2015; Van Hoof and Kraus, 2017) most of them however have mainly focussed on the Northerly areas, with little focus on the Mediterranean region. The reasons for this may be found in the struggle that Mediterranean scientists face when promoting their scientific findings outside their scientific fora, but now the time has come to analyse the issue at a Mediterranean level and provide a different point of view.

In this paper, we will identify some of the main difficulties that the CFP faces in the Mediterranean Sea, using two emblematic case studies in the Adriatic Sea to illustrate our point. The first section will provide a general overview of the two fisheries and the stock status in the area, including main regulations and management strategies of the last decade. The second section will focus on the process currently in place—in the Mediterranean in general and in the Adriatic Sea in particular—for the management of marine resources, and how science is translated into advice. The main bodies in charge and their current and ideal roles will be described. The third section will identify the main flaws of the current system, but will also describe how, after decades of apathy, the efforts made in the most recent years are slowly showing their fruits. Finally, the fourth section will provide our view on the measures that could help achieve the objectives of the CFP before 2020, given the current situation in the Mediterranean.

SETTING THE SCENE

The Development of the Fishery

The current fishing pattern in the Mediterranean Sea is the result of a long history of exploitation of marine resources which started several thousands of years ago (Farrugio et al., 1993; Lleonart and Maynou, 2003). Within the area, the Adriatic Sea (**Figure 1**) represents the perfect case study on several aspects of fishery management: a great variety of fisheries, the richness and diversity of species caught and the relative high productivity—especially in the Northern area—(Fonda-Umani et al., 1992), a difficult management due to shared resources (Bastardie et al., 2017), the long history and the long time-series of data (Fortibuoni et al., 2017) and finally its relative isolation from the rest of the Mediterranean.

To understand the context and issues related to the management of such a complex environment, it is important to set the fisheries in their historical, social and political context. Firstly, analogous to what is now happening in several of the coastal Mediterranean countries (e.g., North Africa, Turkey, Syria), the recent past political situation in the Balkan areas has been harsh, with the management of the fishery being irrelevant compared to other problems. Furthermore, similarly to other areas of the Mediterranean, the entrance of Croatia into the European Community is only recent: the past relationship between the two main Adriatic players, Croatia and Italy, thus suffered from the lack of an easy agreement afforded by this political channel, worsened by the fact that fishermen still play an important role in political decisions. On top of that, in Italy the situation has been further complicated by an indiscriminate release of licenses in the past, a weak data collection system until the early 2000s, a general lack of political interest on the issue which often translated into a lack of control, and conflicts between fishermen (northern vs. southern, Italian vs. Croatian, as well as between categories). These circumstances impaired any possibility of common agreements and broad cooperation.

Small Pelagics: Anchovy and Sardine

Small pelagics; i.e., anchovy (*Engraulis encrasicolus*) and sardine (*Sardina pilchardus*), have been, and currently are, the main contributors to total landings for the whole Mediterranean (Lleonart and Maynou, 2003).

Both species have a short life span (about 5–6 years for anchovy and 7–8 for sardine), early maturity, a long spawning period and schooling behavior. Anchovy is an euryhaline species widely spread over the entire basin (Sinovcic, 1978; Palomera et al., 2007; Morello and Arneri, 2009; Zorica et al., 2013). The spawning period goes from April to October (Regner, 1996), with two peaks in May-June and August-September (Regner, 1972; Sinovcic and Zorica, 2006; Morello and Arneri, 2009; Zorica et al., 2013). The main spawning areas are located all along the western coast; few areas have been identified also in the eastern Adriatic (Regner, 1996; Sinovcic, 2000; Morello and Arneri, 2009). The diet is composed mainly by mesozooplanktonic preys (Borme et al., 2009). The spawning period of sardine takes place from late autumn to early spring, with the highest sexual activity in December and January (Sinovcic et al., 2003; Morello and Arneri, 2009), and its more intense in the north-east Adriatic (Morello and Arneri, 2009). Sardines are partially phytoplankton feeders and can digest phytoplankton cells as well as copepods (Grbec et al., 2002; Morello and Arneri, 2009).

In the Adriatic Sea, the two main countries contributing to total catches are Italy, targeting mainly anchovy, and Croatia, targeting mainly sardine. The Croatian fishery saw a period of forced closure in the 1990s due to the war in ex-Yugoslavia: when the war finished, the fleet was renewed with the entrance of the big purse seiners that currently constitute the main component of their fishing fleet. Currently, the Italian share of anchovy and sardine accounts for ∼30% of total national catches; in Croatia small pelagics represent about 80% of the total national catches (EU, 2016). Both species are fished all year round by pelagic trawlers and purse seiners covering great part of the basin, but mostly concentrated in the Northern part (**Figure 2**). Landings of anchovy have followed cyclic fluctuations over the years, with very high values in the late 1970s-early 1980s, partly attributed to the availability of subsidies from the European Community, and again in the late 2000s; both peaks were followed by a more or less marked decline (Carpi et al., 2015). The first, dramatic collapse was recorded in 1987 and has been attributed primarily to 2 years of very low recruitment, result of adverse environmental conditions: the fishery might have played a role in the disruption of the stock, nevertheless, the decrease in biomass started well before relevant changes in fishing effort were recorded (Santojanni et al., 2006). Sardine landings, on the other hand, after enormous values at the beginning of the eighties around 90,000 tons, decreased dramatically until 2005, when they reached the historical minimum of 1,900 tons. Landings then increased again, booming in 2007, mainly due to an important increase of the Croatian fisheries, hitting the second highest value of the entire time series in 2014, at 82,000 tons. Grbec et al. (2002) associated the increase and successive decline of sardine before 2000 to changes in the advection of Levantine Intermediate Waters (LIW) due to climatic fluctuations.

During and after both events, little or no action was taken by the competent authorities to regulate effort to allow the stock to recover, or to minimize potential losses in fishing opportunities

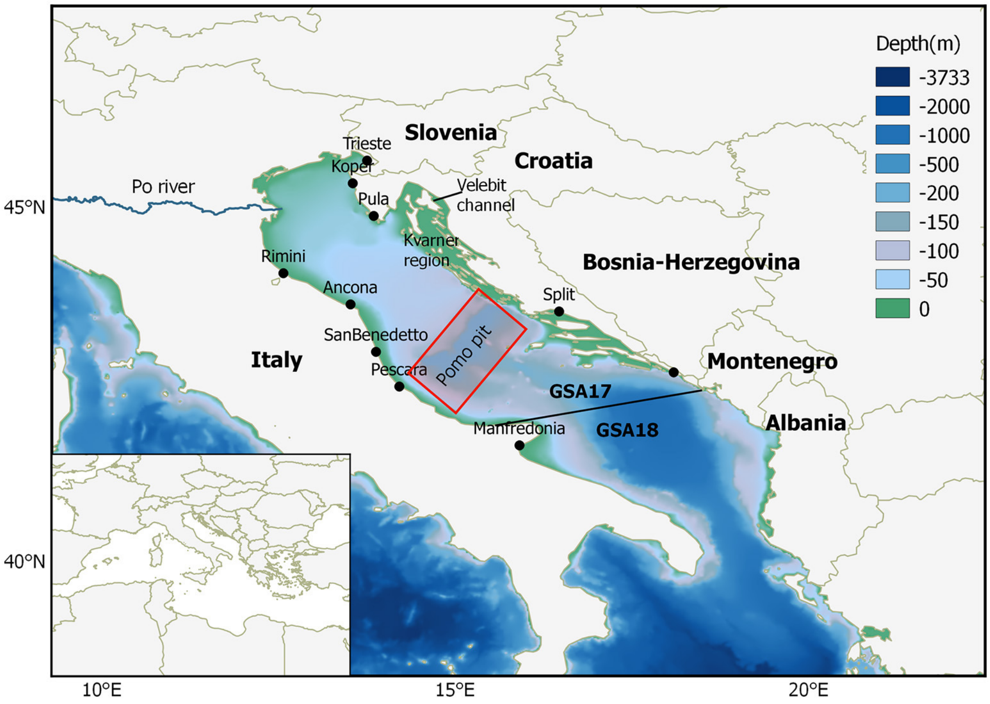

FIGURE 1 | Map of the Adriatic area (in relation to the Mediterranean region). Countries and GSA boundaries as well as main ports and sites cited in the text are highlighted.

in hypothetic future situations of impaired recruitment. The consequences of this apathy are now evident: the Italian sector, whose fishery has always focussed on anchovy, is now suffering, with a decrease in the number of vessels and a general feeling of dismay. The Croatian fleet, targeting mainly sardine for tuna farms, is still stable: it is, however, natural to wonder for how long an already suffering stock of sardine will be able to sustain such harvest rate; the use of low-value (in marketing terms) whole feed-fish species for the growing and fattening of tuna in Croatian waters with locally caught sardines is a practice that is unlikely to be sustainable in the long term, with a food conversion ratio that, at best, is equal to 12.5:1 (Allan, 2004).

In defense of the authorities, it must be said that scientists, despite suggesting a reduction of fishing pressure for many years, have not been very emphatic about this. This has been partly due to the lack of a formal framework to enable specific action, but also to disagreements within the scientific community and possibly to the sometimes overbearing political influence of national administrations on scientific matters.

Although it is unquestionable that environmental variables play an important role for the stock development of pelagic species, it is also true that the exploitation pattern to which the two stocks have been subjected in the last 15 years is unsustainable, with values of fishing mortality estimated by stock assessment models that are beyond safe limits. The current situation, with huge catches for sardine well beyond precautionary levels, a general struggle of the anchovy stock with current F being above the F_{MSY} reference point, and the average landing size of both species in decline, requires strong and immediate action (GFCM, 2016).

The assessment of small pelagics in the Adriatic Sea has been carried out since the eighties, with a well-established sampling program that for many years extensively covered all the fishing ports on the Italian side, together with some sampling along the Croatian coast. An acoustic survey is available for the Italian side from the 1970s, and from 2004 the whole area has been covered to assess the status of these stocks and to keep enhancing the knowledge available on these species (MEDIAS, Mediterranean Acoustic Survey). These are the longest and richest time series of data available in the Mediterranean and have made these two stocks the focus of several debates and management experiments. The stock assessment, historically carried out using a single species VPA-type model, in the last decade has undergone significant changes: the methodology moved to a more sophisticated statistical catch at age model (SAM), and the whole dataset has been entirely revised to improve the quality of the results and provide more accurate scientific advice (GFCM, 2014, 2015). However, the biggest improvement lies in the fact that these stocks have been the guinea pig for a series of processes that are meant to become common practice in the region, following the ICES example: their stock assessment was subjected to a benchmark process (GFCM, 2015), the EU prepared a multiannual management plan for the management of these stocks that has been adopted with recommendation GFCM/37/2013/1 of the General Fisheries Commission for the Mediterranean (GFCM), and a Management

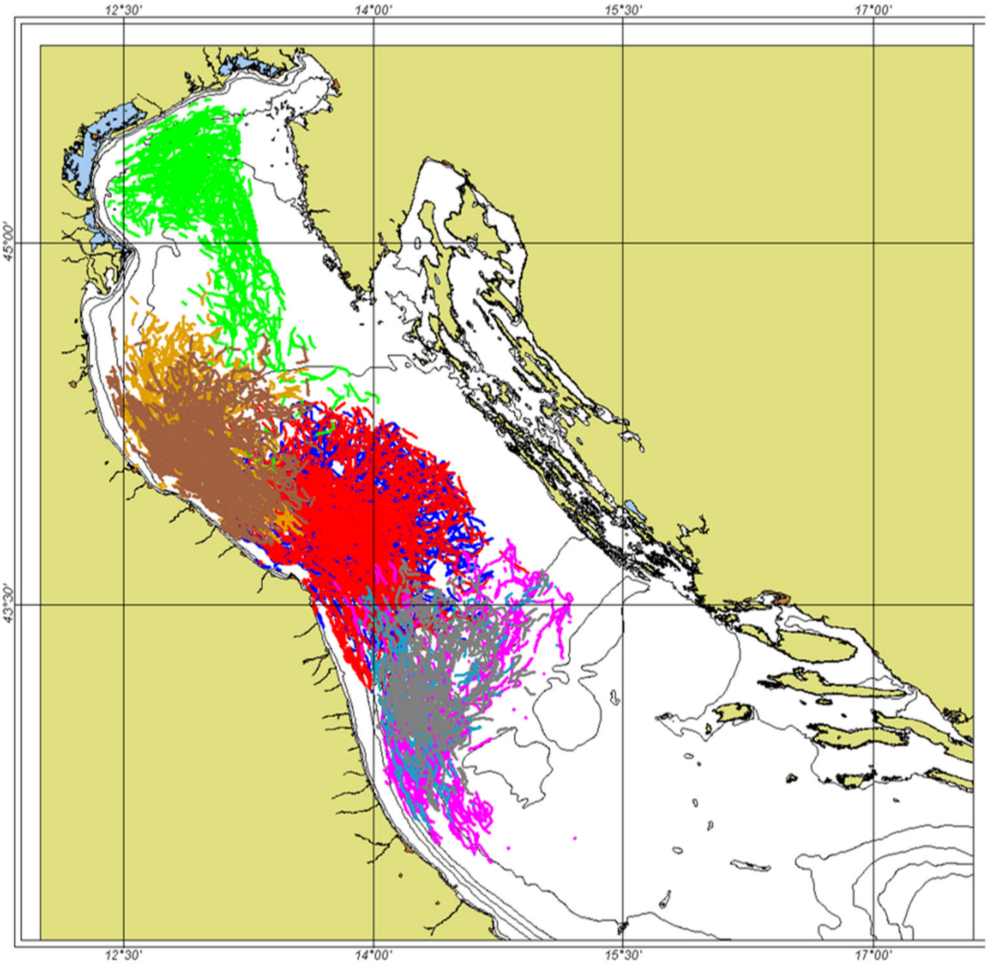

FIGURE 2 | Haul tracks of Italian pelagic trawlers and purse seiners (gray and purple tracks) monitored through a Fishery Observing System (Carpi et al., 2014). The maps represent 5 years of data for eight vessels belonging to the main Italian ports targeting small pelagics.

Strategy Evaluation (MSE)-like process was initiated in 2015–2016 and is still ongoing (GFCM, 2016). Due to the amount of data available, to the high value of the fisheries and the high political interest for the shared nature of these resources, the EU has, lately, focussed a lot of attention and invested plenty of resources on these stocks: this has surely had some positive effects, however we think that this effort has not always been properly channeled, and would have been more effective with the constant involvement of the right parties and a continuous collaboration with the bodies involved.

Norway Lobster

Norway lobster (*Nephrops norvegicus; Nephrops* hereafter), is the most valuable crustacean species landed in the Adriatic Sea (Vrgoč et al., 2004). This species is exploited on muddy seafloors prevalently by means of bottom trawls and to a lesser extent, in smaller areas (e.g., the northern-eastern Adriatic channels), by means of baited traps (Vrgoč et al., 2004; Ungfors et al., 2013). In the Adriatic Sea, it occurs on muddy (silty-clay) grounds at depths from around 50 m to over 400 m (Artegiani et al., 1979; Wieczorek et al., 1999), with important concentrations occurring around 70 m depth off Ancona, around 220 m depth in the Pomo pit and in the Velebit Channel, Kvarner and Kvarnerić region along the Croatian coast (Karlovac, 1953; Crnković, 1964, 1965; Froglia and Gramitto, 1981, 1986, 1988; IMBC et al., 1994; Froglia et al., 1997). Trawl nets and baited traps sample different portions of the population: trawls will only catch individuals when they happen to be outside of their burrows, whilst the bait in traps entices animals out of their burrows meaning they can also catch berried females (Morello et al., 2007, 2009).

Nephrops are bottom-dwellers building complex burrows in muddy sediments; emergence from their burrows varies with time of day, season, animal size, sex, and reproductive status (Froglia, 1972; Atkinson and Naylor, 1976; Naylor and Atkinson, 1976; Aréchiga et al., 1980; Chapman, 1980; Froglia and Gramitto, 1986; Tuck et al., 2000). In particular, emergence follows diel and seasonal patterns with peaks of daily emergence differing according to depth (Bell et al., 2007) and seasonal ones depending on sex (females who do not leave their burrows during the egg-bearing period; Marrs et al., 2000, 2002; Bell et al., 2007).

This all means that the trawl fishery exploits the population selectively and in a different manner according to sex. These factors all affect the availability of *Nephrops* to trawls, their absolute catches and the sex ratio of animals caught. This is particularly important when considering that the main index of abundance available for Mediterranean demersal resources is a trawl survey; i.e., the MEDiterranean International Trawl Survey (MEDITS; Bertrand et al., 2002). Issues with MEDITS are both general (i.e., the survey is designed in such a manner as to not be efficient at catching *Nephrops*) and GSA-specific (the survey in GSA 17 does not follow the spatio-temporal protocol in all years, notable examples being 2007 and 2014—**Table 2**), and it suffers the same problems as the trawl fishery with respect to the burrowing behavior of the species (see STECF, 2016b for details).

The main actors in the trawl fishery for *Nephrops* in the Adriatic are Italy and Croatia, with Italy fetching by far the highest catches since the 1970's (FAO, 2011–2017). The contribution of Croatia to total Adriatic landings, on average, accounts for 25% in weight. Total catch has been characterized by marked fluctuations throughout the years; in Italy, this peaked around 2,000 tons in 2005 and has followed a decreasing trend since. Very little information is available for the Croatian trap fishery, which is an artisanal activity carried out mainly in channel areas of the northern Adriatic.

The geographic distribution of *Nephrops* is highly discontinuous because heavily dependent upon sediment composition which should be muddy and preferably medium-grained (around 40% of clay and silt) (Farmer, 1974; Afonso-Dias, 1998; Bell et al., 2007). Importantly, there seems to be a stock-specificity to the relationship between burrow density and sediment composition which has been found to hold true over time (Campbell et al., 2009). This aspect, added to the fact that *Nephrops* is a sedentary species (Chapman and Rice, 1971), means that *Nephrops* is generally characterized by spatially segregated populations (or stocks) with little or no exchange between them (Bell et al., 2007). Heterogeneity in distribution is also present within smaller areas, giving rise to smaller "subpopulations" or "stocklets" (Chapman and Bailey, 1987) with different densities and life-history characteristics (Maynou and Sardà, 1997; Bell et al., 2007). This appears to be exactly the case of the Pomo/Jabuka pit in the central Adriatic Sea (**Figure 1**): here, growth rates have been reported to differ markedly from other Adriatic areas (Froglia and Gramitto, 1988; IMBC et al., 1994), fact which, paired with the oceanographic characteristics of Pomo/Jabuka, results in a "subpopulation" of smaller, slower-growing animals. Consequently, it is very likely that treating and assessing the *Nephrops* population at a GSA (GFCM Geographical Sub Area) or joint GSA level may be questionable and could lead to an inaccurate and imprecise evaluation of the status of the resource. Furthermore, the assessment of *Nephrops* is fraught by a number of difficulties, from the lack of reliable age-determination methods, to the marked sexual dimorphism, the definition of the functional units, the uncertainty about growth, and their burrowing behavior that results in different selection patterns. Moreover, the lack of spatially explicit catch data complicates the assessment issue further as it has been found that Italian southern Adriatic trawl fleets (GSA 18) often fish in the Pomo/Jabuka pit (GSA 17) and land in GSA 18, withdrawing any reference regarding the spatial origin of the catches (Russo et al., in press).

Attempts to analytically assess *Nephrops* have passed from the initial use of length cohort analyses (LCA) (GFCM, 2009) relying on the unrealistic equilibrium assumption (Dobby and Hillary, 2008) to dynamic assessment models such as VPA, eXtended Survivors Analysis (XSA; Shepherd, 1999) being the most common. VPA-like methods are age-based and thus, in the case of a species that cannot be aged directly, catch-at-length is sliced into catch-at-age on the basis of the growth function assumed: this simple selection of ages from a growth curve is not sufficient given the fact that the growth of *Nephrops* is sex and stage-dependent, that these animals are long-lived (14+ years old), and given the absence of strong modes in catch data. These methods result in imprecise estimates of most recent numbers and are not capable of accounting for growth variability (Dobby and Hillary, 2008; Edwards et al., 2012). In the Adriatic Sea, *Nephrops* was assessed using XSA in GSA 17-18 in 2016 (STECF, 2016b) and in GSA 18 in 2015 (STECF, 2015), and using a production model (Surplus Production in Continuous Time, SPiCT) in GSAs17-18 combined (STECF, 2016a). Despite good diagnostics, the former XSA assessment was deemed not acceptable owing to the flawed scientific assumptions it was based upon, among these: (i) it was carried out on the entire GSA not accounting for differences in the Pomo/Jabuka pit, and (ii) the XSA methodology—which was imposed by EC Joint Research Centre (JRC)—EC Scientific, Technical and Economic Committee for Fisheries (STECF) against the opinion of the expert carrying out the work—was unsuitable. Similarly, the SPiCT production model, which was used to provide the latest scientific advices in the STECF framework, is not in line with other models used around the globe for the same species; besides the outcomes provide a worringly optimistic status of exploitation ($F/F_{MSY} = 1.3$) if compared with other *Nephrops* stocks in the Mediterranean; finally, it is not considered to be adequate to the biology and fisheries of *Nephrops* and should therefore be abandoned.

Explicit length-structured, sex-, fleet-, and area-based integrated assessment methods, directly using length data in the form of size-transition matrices (or using a fully integrated statistical slicing) and fishery-independent surveys or commercial LPUE information for tuning, have been put forward as alternatives (ICES, 2013). Efforts have thus been made to estimate Italian catches within and outside the Pomo/Jabuka pit (Russo et al., 2011, in press) and integrated stock assessment methodology such as CASAL (Bull et al., 2005) and Stock Synthesis (SS3; Methot and Wetzel, 2012) are being attempted in the Adriatic Sea, but have yet to be submitted and validated. In advocating the devil's work, the use of transition matrices, and the results yielded in terms of F, are heavily dependent upon, and confounded by, the growth function assumed (Dobby and Hillary, 2008): in other words, the dog seems to chase its own tail.

Thus, despite some authors advocating analytical methods such as LCA and XSA as yielding the most "realistic and

TABLE 1 | (A) Participation of EU and non-EU countries to GFCM Working Group on Stock Assessment of Demersal species (WGSAD) and GFCM Working Group on Stock Assessment of Small Pelagics (WGSASP); **(B)** Participation of EU and non-EU countries to STECF Working Group (Mediterranean Assessment part I and II).

(A) Participants to WGSAD and WGSASP (excluding Black Sea)

		2012	**2014 I**	**2014 II**	**2015**	**2016**
WGSAD	EU	11	12	27	4	30
	Non-EU	6	7	9	9	10
WGSASP	EU	7	13	13	13	18
	Non-EU	6	4	5	9	7

(B) Participants to STECF-Mediterranean Assessment (Part I and II)

		2012-I	**2012-II**	**2013-I**	**2013-II**	**2014-I**	**2014-II**	**2015-I**	**2015-II**	**2016-I**	**2016-II**
EWG	EU	18	19	20	20	21	19	21	21	13	13
	Non-EU	0	2	0	0	0	0	0	0	0	0

TABLE 2 | Temporal distribution and number of hauls for the Medits trawl survey in the Adriatic Sea from 2000 to 2016.

Year	**Italian survey**			**Croatian survey**		
	Starting date	**End date**	**No of hauls**	**Starting date**	**End date**	**No of hauls**
2000	08/06/2000	02/08/2000	88	26/06/2000	02/07/2000	47
2001	11/06/2001	05/07/2001	88	25/05/2001	31/05/2001	48
2002	17/07/2002	26/09/2002	121	02/09/2002	11/09/2002	59
2003	17/06/2003	12/08/2003	121	20/06/2003	26/06/2003	59
2004	29/06/2004	11/08/2006	120	02/08/2004	08/08/2004	61
2005	29/06/2005	27/09/2005	121	01/08/2005	08/08/2005	59
2006	05/07/2006	18/08/2006	121	25/07/2006	01/08/2006	59
2007	12/06/2007	17/07/2007	122	26/06/2007	03/07/2007	60
2008	11/06/2008	31/07/2008	123	12/07/2008	22/07/2008	59
2009	07/05/2009	07/06/2009	123	24/07/2009	30/07/2009	60
2010	01/06/2010	16/07/2010	122	23/06/2010	30/06/2010	60
2011	03/06/2011	04/08/2011	122	29/06/2011	06/07/2011	60
2012	20/04/2012	18/08/2012	122	16/07/2012	24/07/2012	60
2013	10/06/2013	01/08/2013	122	03/07/2013	18/07/2013	59
2014	14/08/2014	23/11/2014	180	05/07/2014	06/08/2014	56
2015	16/07/2015	20/08/2015	180	03/07/2015	19/07/2015	66
2016	15/08/2016	20/09/2016	180	04/07/2016	21/07/2016	56

reliable" population estimates for *Nephrops* (Sardà et al., 1998; Sardá and Aguzzi, 2012), the issues with slicing and others related to the fact that they assume little or no mis-reporting of catches, have led ICES to stop the use of analytic assessments. This was done in favor of the direct use of Under Water TV survey (UWTV) data to provide absolute estimates abundance to which harvest rates are applied to recommend catch and landings (ICES, 2013). This is now the standard and ICES strongly recommends the development and use of UWTV surveys where *Nephrops* assessments are required (ICES, 2013). A yearly UWTV survey covering the Pomo/Jabuka pit area in the Adriatic Sea was established jointly between Italy and Croatia in 2009 and has been ongoing since. This survey is partly funded by the FAO-AdriaMed regional project, but it is generally not supported by national or European funds and for this reason it is spatially restricted to the Pomo/Jabuka pit, preventing these data from being usable for a GSA-wide evaluation of *Nephrops*.

Management History: Legislations

This chapter will not try to cover all legislation in place in the Adriatic Sea, but aims to provide an overview of the main regulations that have affected and currently affect the Adriatic small pelagic and demersal fisheries. Several multilateral environmental agreements, which may indirectly impact these two fisheries, have been adopted but will not be considered here since they are not relevant to the scope of this paper. Italy and Slovenia, initially as part of the European Economic

Community (ECC) and subsequently the European Community, which was afterwards absorbed into the European Union, need to follow EU regulations: Member States can take measures for the conservation of the stocks in waters under their sovereignty, as long as these are not less restrictive than the EU regulations in place. In 2001, Croatia signed a "Stability and Association Agreement" with the EU; i.e., a formal commitment toward the integration of the EU *aquis,* which bound the country to the acceptance of the Common Fisheries Policy (CFP). This agreement did not stop Croatia from undertaking, since 2004, an important fleet renewal, with the construction of new vessels and a net increase in capacity of the fleet. In addition, the Croatian government attempted to establish an Ecological and Fisheries Protection Zone (EFPZ) that was somehow against the agreement contained in the CFP, having the potential for the exclusion of EU fisheries within the Croatian zone: after several years of debates and negotiations, in 2008 the EFPZ was enforced, with a special derogation for EU vessels. Despite the improvement in most recent years, in particular after Croatia joined the EU, Croatia is still highly influenced by internal politics and dynamics (Mackelworth et al., 2011).

Hand in hand with EU regulations, the framework of National regulations in Italy has historically acted to control several aspects of the fisheries, such as the number of issued licenses, gear characteristics, technical features of the fishing vessels, spatial and temporal restrictions. A similar approach was adopted by Croatia, whose main pieces of legislation were drafted in 2000 and 2006 and regulate fishing zones through fishing effort and fishing capacity in terms of gears, temporal and spatial restrictions, and species protection (AdriaMed, 2007).

In line with these legislations, following the directives included in the reformed CFP, as well as the pressure from the scientific community and the worries of the fisherman themselves, recent measures have been enforced for both small pelagic and demersal fisheries. Recently, a series of measures stemming from GFCM recommendations (Rec. GFCM/38/2014/1, Rec. GFCM/39/2015/1, Rec. GFCM/40/2016/3), have been adopted: a reduction of the number of fishing days for both anchovy and sardine to a maximum of 144 days; the closure, in Italy, of the 6 mile strip along the entire coast for 6 months from 1st July to 31 December and a closure in Croatia of the inner seas for 6 months in 2016 and again in 2017, from 1 April to 30 September; extra temporal closures between 1 October and 31 March for sardine and between 1 April and 30 September for anchovy; as well as the imposition of catch and fishing capacity limits for both species. Further, an area of the Pomo/Jabuka Pit, which is an important nursery area for European hake and hosts a resident population of Norway lobster—was closed to the trawl fishery for 15 months in 2015/2016. Since October 2016 it is open to a limited number of authorized bottom trawlers and closed to bottom longliners. This measure, which mainly affected Italian vessels, was associated with the development of a specific monitoring program that started in 2015 and it is planned to be carried out every year (Colloca et al., 2015).

All these measures seem like an attempt to answer to a sudden and long-delayed increasing pressure from the EU, whose focus for the Adriatic region has grown since Croatia joined. The General Fisheries Commission for the Mediterranean (GFCM) has fully come on board, setting its target to reverse the declining trend of Mediterranean stocks by 2020 through their ambitious mid-term strategy, and, more specifically, recommending that exploitation levels of small pelagic species in the Adriatic Sea be at the maximum sustainable yield by 2020 (Rec. GFCM/40/2016/3). However, to comply with these 2020 MSY objectives and definitely align with the regulations included in the new CFP, action may have come too late.

THE CURRENT MANAGEMENT

Bodies Involved

The main players of the management of marine stock in the Mediterranean Sea can be divided in four big entities: (i) the Food and Agriculture Organization (FAO) with its own Regional Fisheries Management organization (RFMO), the GFCM, as well as its Scientific Advisory Committee on Fisheries (SAC) and regional projects, (ii) the European Commission (EC) and its bodies (i.e., STECF and JRC), (iii) the national authorities and iv) fisheries associations coordinated by the MEDiterranean Advisory Council (MEDAC) (**Figure 3**).

The GFCM, established in 1949, is the official RFMO of the Mediterranean and Black Sea and it is part of FAO. The main purpose of GFCM was to promote the development, conservation and rational management of marine fishery resources in the Mediterranean and the Black Sea, creating a common ground for discussion for European and non-European countries. In 1997, it became a Commission and since then it has the authority to adopt binding recommendations for fisheries conservation and management in its area of application, and plays a critical role in fisheries governance in the region. The recommendations of the GFCM become compulsory for each individual Member State once they have notified. The GFCM receives scientific input from the SAC whose mandate is to provide independent advice on the technical and scientific basis for decisions related to fisheries conservation and management.

Hand in hand with the GFCM, the FAO regional projects operate in the Mediterranean to connect countries and sub-regions to promote and support the conservation of marine resources. In the Adriatic Sea, the main player is the AdriaMed regional project: born in 1999, it has now a catalytic role in encouraging cooperation aimed at fisheries management in the area.

The Directorate-General for Maritime Affairs and Fisheries (known as DG-MARE) is the right arm of the European Commission when it comes to the implementation of the CFP and the Integrated Maritime Policy. DG-MARE receives scientific inputs to implement the common fisheries policy from ICES, whose competence area is Northern Europe, and the STECF, an EC body that is meant to be the EC scientific forum and operate in all the areas under EU control, including the Mediterranean.

The national authorities (such as ministries and port authorities) have the main role of implementing the regulations established by the GFCM and the EU. In Italy and Croatia,

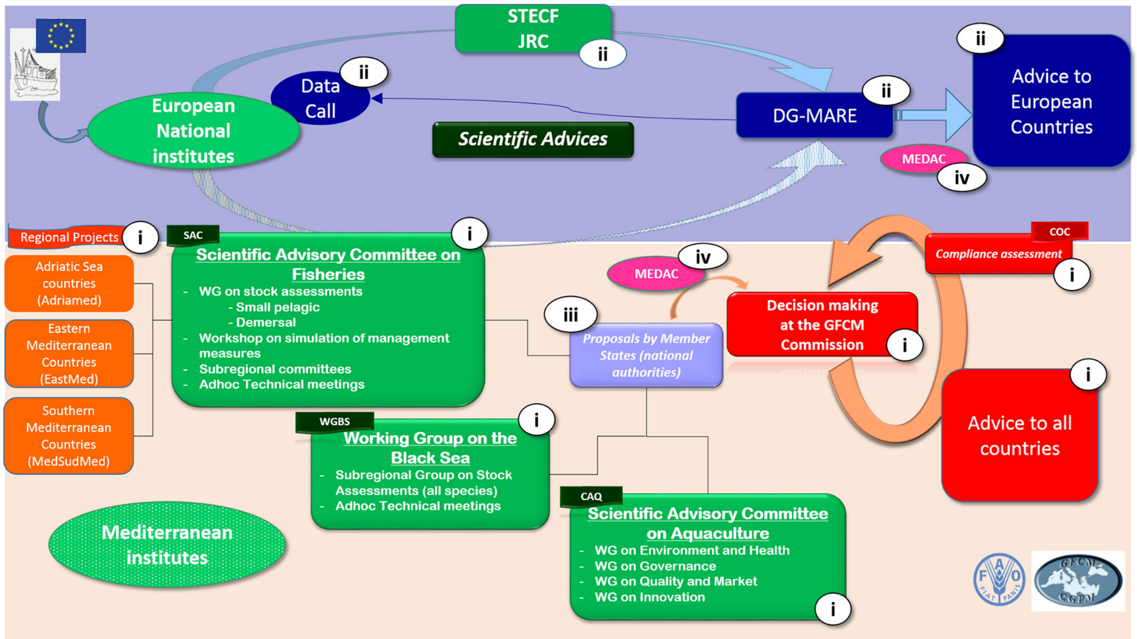

FIGURE 3 | Management process in the Mediterranean Sea. Roman numbers match the order used in the text. Coloring: green boxes refers to scientific bodies; red boxes refer to FAO bodies; blue boxes refer to EU bodies; pink boxes refer to stakeholders.

the fisheries directorates under the Ministry of Agriculture are responsible for carrying out this task. These are the competent authorities for Monitoring, Control, and Surveillance (MCS).

The governments regularly convene the sector to inform them of the resolutions and changes that affect or may affect the fishery. The fisheries sector participates in the MEDAC. The MEDAC is made up of European and national organizations representing the whole fisheries sector and other interest groups (such as environmental organizations, consumer groups, and sports/recreational fishery associations) which operate in the Mediterranean area within the framework of the CFP. The role of MEDAC includes the preparation of opinions on fisheries management and socio-economic aspects in support of the fisheries sector in the Mediterranean. Such opinions are submitted to the Member States and the European institutions in order to facilitate the achievement of the objectives of the CFP; MEDAC also proposes technical solutions and suggestions, such as joint recommendations (ex. Art. 18 Reg.1380 / 2013) at the request of the Member States.

The Stock Assessment Processes: Main Criticism

Currently, in the Mediterranean, the stock assessment process is carried out on two levels. First and foremost, as it includes all Mediterranean riparian countries and not just EU Member States, at the level of the GFCM-SAC Working groups: in general, the FAO-regional projects help with the process, coordinating the member states, easing the availability of the data among countries, and supervising the assessment process to make sure that an agreement is reached before presenting the results to the dedicated GFCM working group. Importantly, within this entire process, full flexibility is given to the experts in matter of data and assessment methods used toward obtaining the best possible outcome, given the information available and the scientific assumptions considered acceptable for the species in question. The working group is then charged of critically revising the assessment in terms of data used, assumptions made and results obtained and ensure that the assessment is correct from a scientific point of view. Finally, the results of the working group are presented to and approved (or not) by the SAC before arriving on the GFCM Commission table. The GFCM then, on the basis of what has been recommended by the SAC, together with the national authorities and including the EU, which is a Contracting Party, decides on the specific measures to be taken. In parallel, assessments of EU Member State stocks are also carried out by the STECF through working groups specifically devoted to the Mediterranean Sea. The process is similar to that adopted by the GFCM-SAC in that the STECF calls on experts (hired to act as consultants) to carry out the assessment of selected species for which official data—which have been prepared following the specific guidelines decided by DG-MARE—are provided at the time of the meeting. The whole group is then called to evaluate the work done, resulting in the assessments being accepted or not. If accepted, the assessments proceed to the table of the STECF plenaries where they are scrutinized by STECF members, which are very often the same experts who carried out the assessments. The scientific advice of the STECF is then available for EU managers and can be used in a wide framework of policy actions [from the balance of fishing capacity and fishing opportunities, to the Marine Strategy Framework Directive (MSFD)].

The process as it is should be enough to efficiently respond to the need for a proper management of the resources. However, complications arise because the two bodies (i.e., GFCM and STECF) find themselves in charge of the same pieces of work (often producing different assessment and advice for the same stock), overlapping with each other's mandate, without a clear distinction of their respective roles; this situation is very delicate and requires strong actions, new agreements and coordination from all sides, conditions not always easy to achieve. As a matter of fact, the current lack of coordination between GFCM-SAC and STECF-DGMARE-JRC has hindered the assessment of some Mediterranean stocks fuelling the difficulties related to the already complex process of aligning management in the Mediterranean with the CFP and the MSY target.

In addition, the specific requirements of the CFP and in general of the whole management process, are becoming more and more complicated: this increased complexity not only demands for new and more advanced stock assessment approaches to be used (e.g., integrated assessment, ecosystem models and management strategy evaluation), but also require enormous amounts of data (i.e., genetic, movements, fleet based information, estimates of natural mortality, and growth etc.), not always equally available throughout the area, while concurrently demanding more and more expertise from the scientists.

One of the shortcomings of the approach adopted by the European Commission so far has been the poor involvement of non-EU countries in matters of common interests, such as shared stocks: the contribution of non-EU countries to the overall exploitation of the stocks can be substantial (**Figure 4**), but this has not helped to move from a European-centric to a Mediterranean-centric management. This has been true especially for Croatia (before joining the EU), Albania and Montenegro in the Adriatic where the lack of engagement—notably in the past—fuelled a general sense of mistrust and bitter feelings toward every action. An example of this is related to the STECF: its role is clear and well-established with respect to ICES; but it is still ambiguous in the Mediterranean context, mainly due to the poor dialogue with the GFCM until very recently. In our opinion the STECF has been doing a great job and has given a huge contribution in terms of the scientific inputs brought to the Mediterranean community. Our criticisms arise, however, for its reluctance in involving non-EU scientists in the scientific discussion in the Mediterranean context (**Tables 1A,B**) (quite different the situation for the Black Sea) and for a recent tendency of imposing its view and *modus operandi* in scientific fora. In this context, the role of the STECF, supported by the activity of the JRC, officially acting as STECF secretariat, is unclear and appears to be transitioning toward becoming a decisional organ, which in some cases is guiding, rather than assisting, several processes of Mediterranean assessment and management, from data collection to the methods to be used for the assessments and, lastly, in the formulation of scientific advice. Such emerging difficulties are surely due to the historical weakness of GFCM-SAC but also to the uncertain role of the latter with respect to DG-MARE and its scientific advisory bodies (especially when it comes to the role of JRC), and to very little guidance from DG-MARE concerning the strategy to be used to achieve the objectives of the CFP in the Mediterranean. This experience is leaving scientists with the impression of not being free to think and act according to their expertise (as they are, in theory, called to do in these occasions), also due to the tangible mistrust expressed by the EC regarding anything that is done outside its supervision (in line with the same independent thinking mentioned above). This has become evident in the last few years, with the STECF's tendency of duplicating the work of the GFCM-SAC on many occasions, not only jeopardizing the success of management due to a general confusion, but also muddling the efforts and the progress done so far and drifting away from its own purposes. All this said, the situation on the other side is not a bed of roses either: the participation of the scientists to the scientific fora of the GFCM-SAC is not mandatory, no reviewing process has been implemented so far, and the assessments are revised during working groups where more than 30 stocks are discussed over a few days, and in many cases little or no space is left to a comprehensive review of the input data, the methodology used and the output.

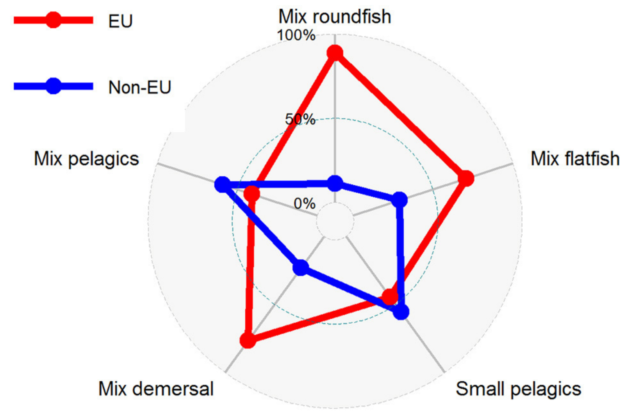

FIGURE 4 | Radar plot of the average (2004–2015) contribution of EU e non-EU countries to the total landings in the Mediterranean Sea (FAO-Fishstat). Croatian data have been included in the non-EU share before 2014, and in the EU share afterwards.

The final goal of the STECF is surely valuable: the methods to get there, however, should be revised and streamlined toward being more considerate of the differences and needs of the countries involved, the specific issues of each region and stock, and in light of the lack of a uniform and centralized authority when third countries are involved. This is where regionalization would become essential toward achieving the objectives of the CFP. In this sense, the GFCM, through the new agreement of 2014, has formally adopted a sub-regional approach to management within the Mediterranean and Black Sea, with the primary objective of supporting sub-regional management plans and identifying sub-regional priorities to support the work of the SAC. The problems encountered are unquestionably part of the process, and both parties have implemented important approaches and processes that can contribute to it, but until they decide to sit together and discuss a common strategy where they become equally supportive one of the other and where the EC realizes that management in the southern areas has different challenges compared to the management in northern Europe, no improvements can be foreseen. The provision of effective scientific advice for the sustainable exploitation of fisheries resources must be transparent and coordinated among the main actors, requiring, in the case of the Mediterranean, a significant change of the current situation: clarifying roles, involving external peer reviewers and nominating yearly (at least) stock coordinators committed to follow the assessment process from the collection of data to the formulation of the management advice.

Recent Evolutions and Successes

There is no progress without struggle, and despite all the problems highlighted so far, we also believe that the situation described above has been the catalyst for a series of important actions and measures that have been taken in the last few years, most notably in the Adriatic Sea. Above all, the requirement that the MSY objective be reached by 2020: its establishment in the new CFP and the pressure from the EU have stimulated some important improvements from both scientific and regulatory points of view, which we will try to summarize below.

In the case of Adriatic Sea small pelagics, the entire dataset used in the assessment—including the biological information provided—was revised through a number of workshops and working groups supported by the FAO regional projects; these working groups also involved the participation of external experts and were organized with the main objective of arriving prepared to the first benchmark assessment proposed and guided by the GFCM. In light of the poor status of both stocks, a management plan (MP), which included a Harvest Control Rule (HCR), was proposed and adopted in 2012. This MP had its flaws (e.g., a harvest control rule of little use since it was going from no measures to a drastic reduction of effort when biomass is below $B_{trigger}$) but was a first important step in the right direction. In order to achieve its requirements, extra emergency measures had to be taken in 2013, 2014, and 2015 by both Italian and Croatian administrations, reducing the number of days at sea allowed (even though the efficacy of this measure is doubtful since the number of days remained still really high), closing areas inside the 6 miles during the spawning period, and adding extra days of closure to the canonical closure period. 2016 has seen the establishment of the first tentative quota system for anchovy and sardine in the Mediterranean Sea: despite the value of this quota still being too high, it marks the starting point for future updates and is the first example of this kind in the Mediterranean Sea. In 2017, the EC adopted the proposal for a multiannual management plan for small pelagic stocks in the Adriatic Sea which has followed several consultations with stakeholders, scientists and the public. Concurrently, the stock assessment process has been improving, and reference points based on F_{MSY} have been estimated: these have implicitly replaced those included in the MP and have been used in the advice for anchovy and sardine in 2015. Finally, in 2015, under request of the EC, the GFCM initiated a process to perform a Management Strategy Evaluation (MSE) on small pelagics in the Adriatic Sea. The process involved stakeholders from both countries, external experts from Spain, the FAO regional projects and the scientists: a stakeholder consultation was carried out to help defining harvest control rules to be tested, and one technical working group was entirely dedicated to the MSE procedure. Finally, the results were discussed at the GFCM Sub Regional Committee for the Adriatic Sea (SRC-AS). This process was repeated in 2017 and the aim is to include socioeconomic components in a formal MSE process in the future. The close collaboration between SAC-GFCM and STECF is a vital requirement if this exercise is to be successful.

For Nephrops, the main challenges are represented by the biology of the species itself and the structure of the stock in the area: in this respect, the Italian ministry first enforced the closure of the Pomo pit area for 1 year, and subsequently funded a monitoring program to be carried out in the region. In parallel, a process of appraisal and evaluation of the stock and the data available was undertaken and has resulted in scientists, and indirectly the managing bodies, being forced to address and come to terms with important issues. One of those concerned the determination of the geographic scale required for an appropriate evaluation of a stock: the prescriptive notion that Mediterranean stocks should necessarily be assessed on a GSA level was questioned and a methodology was developed to determine Italian catches toward catering for the biological needs of the species (Russo et al., in press). This becomes especially important when the only management measure taken with respect to this species is a spatial one, i.e., the closure of the Pomo pit, but official data are not available at that same scale. It also raises questions on (i) the spatial aspects of data collection (in Croatia for example the statistical data collection is subdivided into smaller areas) and (ii) the appropriateness of necessarily carrying out analytical assessment to manage a species: is management based on a flawed analytical assessment better than management based on direct observations (e.g., the use of UWTV to determine catch limits) or on proxy management of another species (e.g., the management of European hake in the Pomo/Jabuka pit would implicitly serve as a management tool for *Nephrops*)?

We are fully aware that there is still a long way to go to reach a smooth assessment process, an integrated management and an efficient system, but the steps taken not only show a general interest in achieving the result of a sustainable use of the resources, but also manifest the will of scientists to improve their work and their cooperation.

TOWARD THE COMMON FISHERIES POLICY

The management of the fisheries in the Mediterranean is currently facing many challenges and there is no easy solution. The 2020 deadline is getting closer and, despite all the efforts, it is hard to believe that the objectives will be met in time. We feel that the long-discussed issue of regionalization, right now more important than ever, has been forgotten. The next few years will be crucial, but if significant effort is not devoted to solving some of the issues summarized above, this attempt will likely fail. We don't claim to have the silver bullet, but there are certainly some measures that could increase the probability of success, if not by 2020, within a reasonable time frame. Regionalization could contribute to balance preferences across actors and institutions, improve efficiency in the realization and provide more effective policies and measures (Hegland et al., 2012). Regionalization can occur at different levels and in several forms, and we are not here to propose one or the other. There are several examples around the world, both positive and negative, that might show the way and we should learn from the failures and successes of others. Common features to failures of the regionalization approach are (i) unclear prioritizing with conflicts between fishery and conserving species; (ii) lack of transparency, critical review and broad stakeholder involvement in the definition of management measures; (iii) a patchwork of authorities with their own rules and policies lacking a clear and harmonized role (Ocean2012, 2012; Svedäng and Gipperth, 2012; Soma et al., 2015). Following these general lessons, we think that a start would be to restore the original roles, delegating the technical and advisory aspects of the management of the Mediterranean to the GFCM that, from its inception, has had the mission of collating all the Mediterranean countries into a unique body. In this view, STECF would provide technical support, working side by side with the GFCM-SAC, providing experts and revisions when needed. In this supportive role, STECF should encourage the participation of third countries: this would be beneficial to improve collaboration, to restore a general feeling of trust, to help the formulation of more appropriate advice, and, most importantly, to export knowledge and technical expertise to all Mediterranean countries, leveling skills and therefore improving the management process at all levels. The EU should avoid intervention in the scientific discussion and provide, on the other hand guidance in the technical aspects and capacity building, with clear terms of reference and coordination. This structure, equivalent to archetype 2 proposed by Hegland et al. (2012), hypothesizes considerable authority placed with the GFCM, in order to allow it to develop different approaches to management according to the needs of the countries involved, with the EU maintaining a coordinating role as well the ability to set the overarching goals and the frame for the regional approaches. This setting could be beneficial toward the achievement of an Ecosystem Approach to Fisheries Management helping and guiding the process to reach common agreements on matters such as indicators and methodologies or Good Environmental Status assessment within Mediterranean countries, whose lack of coherence has been seen as a potential impediment to the realization of the objectives of the CFP (Raicevich et al., 2017). Possibly, another outcome of this type of management would also be to reduce the gap between the decision-making body and the place where the management takes place and would favor the communication with third countries taking advantage of a framework that already foresees and facilitates that. In this respect, the GFCM should improve by all means its framework, and establish a revision process of all the assessments carried out, in a stepwise manner, from the input data to the final advice, to involve external experts from all around the world.

Finally, the establishment of TAC would be an important step forward in the management process. Input control (i.e., effort control) is the traditional system used for managing fisheries in the Mediterranean Sea, but there is clear evidence that it has not achieved its conservation objectives and has actually failed to control fishing mortality (Cardinale and Scarcella, 2017). Although many studies have focussed on the scientific and institutional caveats of the TAC system (see, Kell et al., 2006; Schwach et al., 2007) a case-by-case shift from effort control to a quota system consistent with MSY principles is advisable in the Mediterranean Sea. In particular, the two fisheries considered in the present study are good candidates for such radical change. In this context, the recent GFCM recommendation GFCM/40/2016/1 imposes a catch (and fishing capacity) limit to small pelagics in the Adriatic Sea. This measure is still "business as usual," as it imposes the limit to be equal to the catches of 2014, which were quite high, for sardine in particular. It is, however, a clear change from a strategic management perspective: not only is it a strong move in the right direction but it also implies a MCS system that is effective in governing the small pelagic fishery production in the area. Of course, such change needs to be appropriately analyzed in terms of socio-economic impacts and must be implemented within a participatory framework. The case of *Nephrops* is more complex but could benefit from a similar approach. It is well-established in other areas that analytical assessments may not be ideal for this species (and in the case of the Adriatic still requires a lot of work on data and methods), so a simpler path based on the determination of catch limits derived from UWTV surveys through the application of harvest rates may be a more effective measure for Adriatic *Nephrops*. The setting up of this process would benefit from the experience matured in ICES areas, but would also require an important scrutiny of the data available at present as well as an expansion of the area covered by the surveys. To this end, the role of a strong and legitimate RFMO would be, again, key: it would act as a facilitator, ease enforcement, and allow access of all countries to the negotiations.

FINAL REMARKS

In this paper we tried, at the best of our knowledge, to summarize the changes and the challenges that Mediterranean fisheries have been facing in the last decade, using two case studies as an example. We are far from having the silver bullet able to solve all issues and bring the Mediterranean close to the 2020 target, but surely there is a very evident need for a common effort from all the parties involved. Regionalization has been put forward as one of the focal points of the new CFP, but we feel that somehow this feature has been lost along the way, despite the CFP anticipates tools to incorporate the regional perspective, e.g., the multiannual plans (Prellezo and Curtin, 2015), and we believe it's worth to work on that. We don't insist in putting forward one scientific and management body or the other, but an efficient use of the available instruments would, with the minimum effort, maximize the yield and surely contribute to achieve the MSY objective in the next decade.

AUTHOR CONTRIBUTIONS

PC conceived the work. All authors wrote and revised the paper.

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Evolution of Future Black Sea Fish Stocks under Changing Environmental and Climatic Conditions

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Here we present a case study toward producing quantitative scientific advice on the application of the EU Common Fisheries Policy (CFP) in the Black Sea. We provide estimates of fishing mortality rates at levels which will lead to rebuilding and maintaining stocks above biomass levels that could produce maximum sustainable yield (MSY) under the IPCC RCP4.5 future climate scenario together with the business as usual (BAU) river discharge scenario. In this study, we have implemented a coupled, basin-scale circulation-biogeochemical model and used its output to feed a food web model to test near-future changes that may be observed in the Black Sea ecosystem under the influence of contemporary fisheries exploitation conditions. In order to test model response to changes in climate and related drivers, the future climate scenario (2015–2020) simulation was compared to the present day (2000–2014) simulation. Likewise, to test the sensitivity of the higher trophic level food web model to changes in fishing pressure, a future estimate of fishing pressure was projected based on its respective contemporary value and applied to each fish stock. Using these models, fishing mortality rates that could produce the maximum sustainable yield (F_{MSY}) in future years 2015–2020 and ensure the long-term recovery of the predatory fish stocks of the Black Sea are predicted. Future projections suggest that all fish stock will decrease in all the regions of the Black Sea except for sprat. Anchovy is expected to show the highest decrease in biomass. Analyses on F_{MSY} estimates show that a significant reduction in fisheries exploitation is required for the sustainable management of the Black Sea ecosystems and the related services. This study, for the first time, presents future stock size, F_{MSY}, and MSY estimates for the Black Sea for 11 fish species. F_{MSY} values are generally lower than estimates of the scientific, technical, and economic committee for fisheries (STECF), mainly because of the explicit food web interactions that the modeling system allows to be considered.

Keywords: integrated ecosystem model, Black Sea, fisheries impact, climate impact, maximum sustainable yield, ecosystem-based fisheries management

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INTRODUCTION

Reliable predictions of changing fish stocks should involve an assessment of changes in environmental factors and climate, as well as consideration of food web interactions. Quantitative approaches for making predictions of marine fish stock development are mostly based on target specie(s) rather than an ecosystem approach. Furthermore, a methodological distinction can be made between statistical and process-based models. In statistical approaches, empirical relationships are developed between a restricted number of biotic (e.g., number of recruits, spawning stock biomass, fodder zooplankton) and abiotic parameters (e.g., sea surface temperature, salinity, atmospheric teleconnections such as NAO) and observations of fish production (e.g., Daskalov, 2003; Llope et al., 2011). Typically, as is the case for most stocks, biotic and abiotic parameters act and interact simultaneously. However, although single-species statistical approaches are helpful for understanding the parameters in the past, they tend to fail for future predictions as the system itself is dynamic and the number of processes and their interactions are in a state of continuous change. When revisited with new data, as in the scope of developing management strategies, statistical approaches typically break down and have in general not proved useful for either fisheries or environmental management (e.g., Myers and Mertz, 1998).

Process-based target species models such as Individual Based Models (IBMs) (e.g., Werner et al., 2001; Paris et al., 2007), bioenergetics models (e.g., Guraslan et al., 2014), Dynamic Energy Budget (DEB) models (Kooijman, 1986, 2000) simulate the dynamics of e.g., feeding, growth, and metabolism, during some or all life stages of a species, sometimes also tracking transport of eggs, larvae, and individuals as a function of hydrodynamic and environmental conditions. Similar to the aforementioned statistical approaches, these tools only address a restricted number of the processes linked to production and are rarely tested against the actual reproductive and growth-related dynamics of stocks. They provide useful information in support of fisheries, but only partially describe the complexity of interactions occurring in marine systems. As ecosystems consists of a large number of interacting components and processes, direct effects of environmental change on a particular component may be compounded by secondary effects arising from the feedback between the different ecosystem components.

Models of Intermediate Complexity for Ecosystem assessment (MICE) provide a link between full ecosystem models and single-species models typically used in fisheries management. MICE incorporate best feature of existing single-species models and has the ability to apply standard statistical methods for parameter estimation and can include ecological interactions based on defined objectives (Plaganyi et al., 2014). However, studies performed using MICE also show the importance of including complex trophic interactions between species and the need for developing food web models or "whole of ecosystem models" to allow evaluation of impacts on a broader set of predators (Plaganyi et al., 2014; Punt et al., 2016).

Food web models not only include a broader set of interactions among species but they also capture most of the major processes and interactions occurring in the sea and permit the assessment of both primary and secondary effects of climate and management changes on selected target species. Furthermore, when driven by the outputs of coupled hydrodynamic-ecosystem models they can also integrate the response of the physical environment, planktonic ecosystems, and habitat to climate change (Akoglu, 2013).

The Black Sea is widely accepted to be one of the basins that is highly impacted by a suite of human-induced stressors in addition to climate change (Oguz et al., 2006). The main stressors include eutrophication and hypoxia, overfishing, and introduction of alien species (e.g., BSC, 2008; Oguz and Velikova, 2010). Combinations of these stressors are considered to be the main cause of the degradation of the Black Sea marine ecosystem, which has undergone dramatic changes since the early 1970s. These changes are also highly influenced by climate change (Oguz et al., 2006) and trophic interactions (Akoglu et al., 2014). For example, climate change modulates primary production in marine systems through several mechanisms: direct physiological responses of organisms to changes in water temperature, water column stability and vertical transport, circulation processes which also distribute the high nutrient land based waters. Without considering all these factors, it is not possible to do an accurate assessment of the future ecosystem development including fish populations, especially considering that an ecosystem under the effect of multiple stressors is highly susceptible to the effects of climate change (e.g., Doney et al., 2012). When developing management strategies and solutions for the Black Sea basin, it is especially important to consider the effects of the changing environment and the changing ecosystem within a single system with interacting components.

Fish stocks in the Black Sea have undergone a series of shifts in parallel to the changes in the environment and increase in fisheries pressure. After the depletion of large and medium predatory fishes, anchovy in particular, and small pelagic fish in general, started acting as the top predators by the early 1970s and were exposed to a major stock collapse at the end of 1980s. During the last 25 years, the southeastern region has been the only part of the Black Sea sustaining noticeable fish stocks. In particular, the small pelagic fishery has been limited primarily to an economically low-value anchovy at a level generally higher than the maximum sustainable catch size (STECF-15-16, 2015). The remaining areas (i.e., the western, eastern, and northern regions) have supported low fish stocks/landings, and have been under a gelatinous-controlled ecosystem state (Oguz et al., 2001).

The recent stock assessment report (STECF-15-16, 2015) gave the most up-to-date status of the Black Sea fishery. In this report, quantitative stock assessments for eight species of commercial fish in the Black Sea were carried out. Only the assessment of turbot and sprat were considered of enough quality to conduct short term forecast. For all the other fish (i.e., whiting, Mediterranean horse mackerel, Black Sea anchovy, spiny dogfish, thornback ray, and red mullet) short term forecasts were not possible. All assessments were considered to be of enough quality to define the status of the stocks in terms of fishing mortality (F) (or exploitation rate, E) with respect to F_{MSY} (the fishing mortality or exploitation rate required to achieve maximum sustainable yield).

The recent scientific, technical and economic committee for fisheries (STECF) report STECF-15-16 advises that for spiny dogfish there should be no directed fishery and for the other stocks (turbot, red mullet, anchovy, horse mackerel, whiting, and thornback ray) catches and/or effort to be reduced until fishing mortality is below or at the proposed F_{MSY} level, in order to avoid future loss in stock productivity and landings.

This paper is designed to provide scientific input for the future implementation of EU Common Fisheries Policy (EC regulation 1380/2013) which aims at implementing a community system for the conservation of marine biological resources and for the management of fisheries exploitation in order to guarantee ecological, economic, and social sustainability. Thus, the results of this paper provide (i) an assessment of the current status (2000–2014) of the Black Sea ecosystem, (ii) changes in ecosystem structure and fish stocks under a future climate scenario including future river nutrient load development (2015–2020), (iii) quantitative advice on fishing mortality rates that would allow rebuilding and maintaining of the fish stocks under changing environment and climate conditions.

METHODS

To assess the current status of the Black Sea ecosystem an end-to-end modeling system consisting of a circulation model, a biogeochemical model, and a higher trophic level model were used to simulate the present day (2000–2014) ecosystem conditions and were validated against available *in-situ* and satellite derived observations. To be able to forecast changes in ecosystem structure and fish stocks in the near future, this end-to-end model was further run with atmospheric forcing generated using a climate model run under the IPCC RCP4.5 emissions scenario together with future predictions of river nutrient loads for the time frame 2015–2020. Below, the details of the modeling system are given, followed by a discussion on model validation, as well as a description of the different simulations used in this study.

Integrated Modeling System

The modeling system used in the study is composed of three models developed, used and validated for the Black Sea in previous EU 7th Framework Programme funded project OPEC (Allen et al., 2014). The different models in the modeling system are coupled with each other through an end-to-end approach with one-way coupling where the currents, mixing, and temperature predictions made by the physical model are fed into the biogeochemical model (**Figure 1**). There they are used to simulate the spatiotemporal distribution of biogeochemical variables including plankton densities and abiotic nutrient concentrations. The biotic components in the biogeochemical model are then fed into the higher trophic level model (**Figure 2**), where they are used as resources for fish and marine mammal populations. The physical model used for the Black Sea is a parallel implementation of the Princeton Ocean Model (POM) called the Stony Brook Parallel Princeton Ocean Model (sbPOM). The biogeochemical model is the Black Sea Integrated Modeling System (BIMS) which includes representations of phytoplankton growth on abiotic nutrients and light, the interaction between phytoplankton and zooplankton communities, the microbial loop as well as the redox dynamics within the sub-oxic zone (**Figure 1**). The higher trophic level model, Ecopath with Ecosim (EwE) includes representation of 11 commercially exploited fish species in the Black Sea (**Figure 2**). These are anchovy, sprat, Atlantic mackerel, horse mackerel, bonito, whiting, turbot, spiny dogfish, shad, red mullet, and bluefish. The dynamics of the higher trophic level organisms are driven by the plankton dynamics provided by the biogeochemical model as well as the trophic interactions between different higher trophic level organisms.

The domain of the physical model includes the whole of the Black Sea except the Sea of Azov with a 4 × 4 km horizontal grid and a 35 level, terrain-following sigma-coordinate, vertical grid. It uses Mellor-Yamada 2.5 turbulence parameterization (Blumberg and Mellor, 1987), incorporates parameterizations for the water fluxes at the Bosphorus and includes nine of the largest rivers that flow into the Black Sea. The physical model was initialized using World Ocean Atlas fields (WOA; Locarnini et al., 2013; Zweng et al., 2013) monthly climatology and spun up for 5 years. Then a hindcast simulation for the 2000–2014 period and forecast simulation for the 2015–2020 period were undertaken.

The biogeochemical model BIMS, is based on a 1D model by Oguz et al. (2001) and an earlier 3-D version of the model (Cannaby et al., 2015). The vertical grid was designed to provide sufficient resolution at the surface and sub-surface layer where most of the biogeochemical dynamics take place. The biogeochemical model contains 30 state variables that include four phytoplankton types, four zooplankton types, oxygen, hydrogen sulfide, inorganic nutrients, and detritus in both nitrogen and phosphorus currencies as well as the carbonate system variables (**Figure 1**). Autotrophs are represented by four types of phytoplankton; bacillariophyta (diatoms; P_d), dinophyta (non-toxic dinoflagellates; P_f), chrysophyta (coccolithophores; P_c), and the small phytoplankton group (P_s) representing picophytoplankton (e.g., *Synechococcus* spp., *Prochlorococcus* spp., picoeukaryotes) and nanophytoplankton (e.g., autotrophic flagellates). Coccolithophores are introduced as a separate group due to their special feature of calcification ($CaCO_3$ formation).

Consumers comprise four zooplankton functional/species groups: the microzooplankton (Z_s) group with a size of <200 mm (dominated by heterotrophic flagellates and ciliates), the mesozooplankton (Z_l) group with a size range of 0.2–2 mm (consisting of copepods, cladocerans, and appendicularians), the opportunistic omnivorous dinoflagellate species *Noctiluca scintillans* (Z_n) and a combined functional group consisting of the carnivorous gelatinous species *Mnemiopsis leidyi* and *Aurelia* (Z_g). The bacterioplankton group (B) decomposes particulate organic nitrogen (D_n) and phosphorus (D_p) to produce inorganic nutrients ammonium (NH_4) and phosphate (PO_4). The model includes a simplified representation of nitrification where ammonium (NH_4) is directly turned into nitrate (NO_3) at a rate dependent on dissolved oxygen concentrations (O_2).

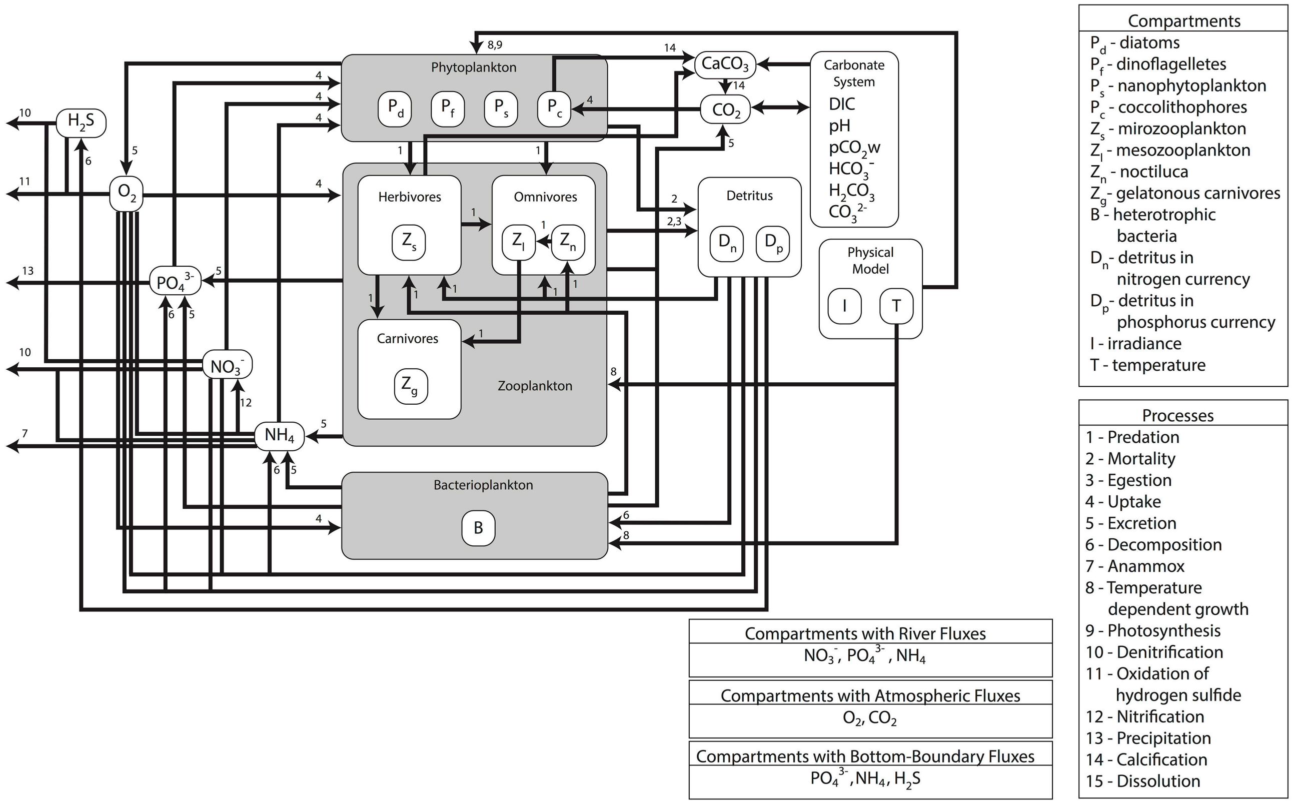

FIGURE 1 | Schematic of the lower trophic level model setup and trophic interactions used in the study. The model includes four phytoplankton groups, three zooplankton groups, two detritus groups, bacterioplankton and nutrients (NO_3, NH_4, PO_4) and a detailed representation of the carbonate cycle.

Hydrogen sulfide (H_2S) is an additional state variable describing the redox processes across the suboxic-anoxic interface. The processes of chemolithotrophic denitrification and anaerobic denitrification are also included in the model and control the upward fluxes of ammonia and hydrogen sulfide and the downward fluxes of nitrate in the suboxic zone. Processes related to the manganese and iron cycles are not represented explicitly, but are parameterized implicitly for simplicity. Carbon dioxide (CO_2) and Calcium Carbonate ($CaCO_3$) concentrations form two state variables of the carbonate module.

The higher trophic level (HTL) model used is the time-dynamic Ecopath with Ecosim (EwE) model of the Black Sea (Akoglu, 2013) (**Figure 2**). In this study, the model is slightly modified to match the biogeochemical model's trophic structure. The model includes 23 functional groups and is parameterized using spatial averages of the required lower trophic level compartments and flows between them as detailed in Libralato and Solidoro (2009). The 23 functional groups (**Figure 2**), are comprised of 11 fish groups; Black Sea anchovy (*Engraulis encrasicolus ponticus*), Black Sea sprat (*Sprattus sprattus phalaericus*), Pontic shad (*Alosa kessleri pontica*), Black Sea horse mackerel (*Trachurus mediterraneaus ponticus*), bonito (*Sarda sarda*), bluefish (*Pomatomus saltator*), Atlantic mackerel (*Scomber scombrus*), turbot (*Psetta maeotica*), spiny dogfish (*Squalus acanthias*), Black Sea whiting (*Merlangius merlangus euxinus*), and red mullet (*Mullus barbatus ponticus*). Anchovy is defined as an ontogenetic group and is separated into juvenile "0" and adult "1+" life stages. Two fishing types were defined: trawlers and purse seiners to represent the fisheries impact on the ecosystem.

In addition, it includes two jellyfish; *Mnemiopsis leidyi*, *Aurelia*, pooled into one group; three detritus groups; one group representing sediment and two representing ammonium and nitrate; two phytoplankton and two zooplankton (non-gelatinous, fodder zooplankton) groups; one bacteria group; and one dolphin group to represent the Black Sea marine mammals, which are composed of short-beaked common dolphin (*Delphinus delphis*), bottlenose dolphin (*Tursiops truncatus*), and harbor porpoise (*Phocoena phocoena*).

The mass-balance model was setup and balanced for the quasi-pristine conditions of the early 1960s. The diet composition matrix of the model was largely based on data available by stomach content analysis and compiled from FishBase (Froese and Pauly, 2011) and based on Akoglu et al. (2014). The specific model setup, concerning the input to the model as well as the diet composition matrix is detailed in Tables S1, S2. The initial EwE model of the Black Sea was run one-way and offline coupled with the BIMS model (**Figure 2**) following the methodology detailed in Libralato and Solidoro (2009).

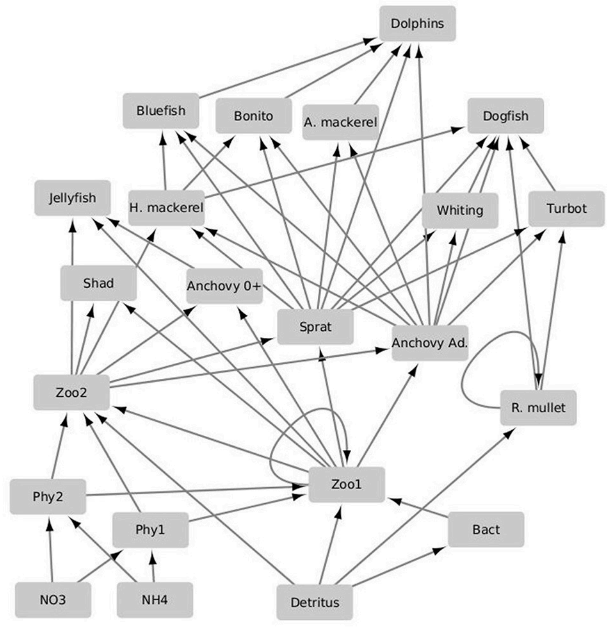

FIGURE 2 | Schematic of the lower trophic level integrated higher trophic level model EwE used in the study. The planktonic and non-living model compartments as well as their related flows and uptakes are referenced to and parameterized according to the biogeochemical model. The arrows denote directions of predatory and uptake flows. Functional groups are abbreviated as follows: Atlantic mackerel (A. mackerel); adult anchovy (Anchovy ad.); larval anchovy (Anchovy 0+); red mullet (R. mullet); horse mackerel (H. mackerel); microzooplankton (zoo1); mesozooplankton (zoo2); dinoflagellates, diatoms and coccolithophores (phy1); nanophytoplankton (phy2); bacteria (Bact), nitrate (NO_3); ammonium (NH_4).

Model Scenarios

Atmospheric forcing for the 2010–2014 period simulation was taken from the COSMO-CLM 14-km spatial resolution (Rockel et al., 2008) atmospheric fields. Atmospheric forcing of the potential future climate scenario (2015–2020) was based on the Intergovernmental Panel for Climate Change (IPCC) RCP4.5 greenhouse gas emission scenario. This scenario represents a future world in which emissions peak around mid-century and predicts a global temperature increase of about 1.8°C by the end of the century (IPCC, 2013). However, considering that the present study is only concerned with the near-future (until 2020), the particular emissions scenario used in atmospheric forcing is expected to be minimally relevant.

River water, nitrate and phosphate discharge rates for the major rivers along the Black Sea were obtained from Ludwig et al. (2009) as well as the Black Sea Commission's river database. In total nine rivers are considered in this study that make up a mean yearly discharge of 320 km^3 yr^{-1}, of which Danube contributes 2/3rd of the discharge and the four major rivers emptying on the northwestern shelf, Danube, Dniepr, Dniestr, and Southern Bug, contribute 89% of the water discharge into the Black Sea. The forecast simulation was undertaken using the "business as usual" (BAU) river discharge conditions considering the anthropogenic pressure acting on the Black Sea. This is one of five different futures of the Southern European Seas that were calculated based on the Millennium Ecosystem Assessment (MEA) (Alcamo et al., 2005). The BAU scenario assumes that fertilizer use efficiency after 2010 does not change and is predicting continuous high nutrient loads of Black Sea rivers.

To assess the regional impact of different climate scenarios, the Black Sea was divided into five different regions that cover three coastal regions (broader northwestern shelf region, southern coast, northeastern coast) as well as the eastern and western inner basins (**Figure 3**). The regions were defined following bottom bathymetry to divide between coastal and deep sea regions. The deep basin was divided into two regions, east and west, roughly following the semi-enclosed circulation features of the eastern and western gyre. The coastal regions were divided to define the northwestern shelf region, the region known to be a nursery region for many fishes of the Black Sea, as well as those regions influenced by the major freshwater input plume from the shelf as the region between Crimea to Zonguldak on the southern Black Sea coast. A second coastal region was defined between Zonguldak and Batumi (Georgia) where the majority of fish catches occur, so it covers the major fishing area important for anchovy and other fisheries. The last region was defined to reach from Batumi to Crimea, which is the second most important fishing ground in terms of catches following the Zonguldak-Batumi region and exploited mainly by the Russian and Georgian fleets.

With the coupled hydrodynamic-biogeochemical model the following simulations were undertaken. The present-day simulation (2000–2014) was performed using the COSMO-CLM 14-km resolution atmospheric fields and the present-day river water, nitrate, and phosphate discharge rates obtained from Ludwig et al. (2009) and the Black Sea Commission's river database. Thereafter, a future climate scenario (2015–2020) was undertaken using the IPCC RCP4.5 greenhouse gas emission scenario together with the BAU river forecast scenario. The outcomes of the two periods were then compared to assess the influence of climate variability on the ecosystem in the defined regions.

With the Ecopath with Ecosim model the hindcast scenario (2000–2014) was performed using primary productivity from the biogeochemical model and fishing mortality values for exploited species from STECF report (STECF-15-16, 2015) as forcing. The present-day simulation results were fit to the catch statistics and Extended Survivors Analysis (XSA) stock estimates for fish groups from the STECF report and biogeochemical model outputs for plankton groups. The future scenario (2015–2020) was run utilizing projected primary productivity from the biogeochemical model and constant contemporary fishing mortality values of 2014 until 2020 as forcing throughout the simulation. The outcomes of the two periods were then compared to assess the influence of climate variability in the defined regions.

Once the EwE model was fit to observations and validated, varying fisheries exploitation levels were investigated to obtain F_{MSY} values for exploited species utilizing the EwE MSY routine for each year between 2000 and 2020. The management strategies suggested in this study are based on these results. The

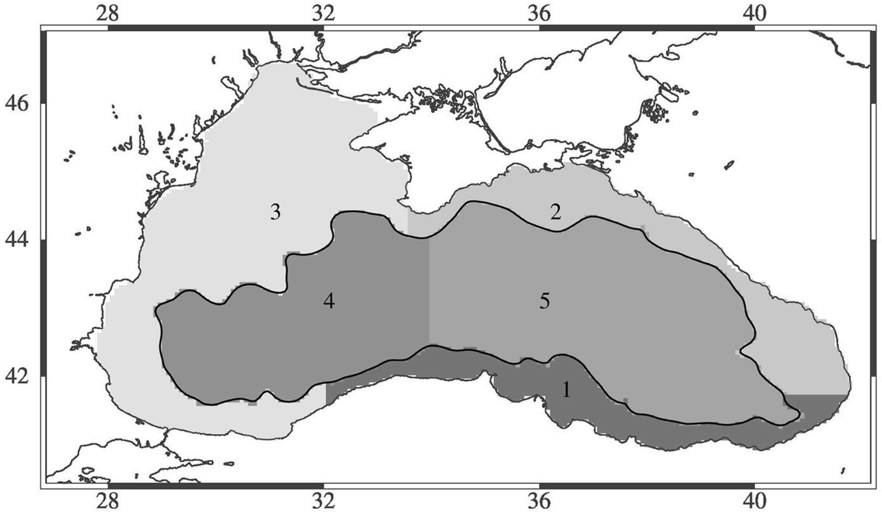

FIGURE 3 | Map of the Black Sea showing the five different regions assessed in this study.

methodology applied in this study is the "multi-species F_{MSY}" search routine of EwE model. This routine simulates the Ecopath food web model over time under dynamic trophic interactions with varying fishing mortalities for the functional group in question, i.e., the one for which F_{MSY} is being searched, while keeping the fishing mortalities of all other species as constant at the level of the initial Ecopath mass-balance. It runs the model to equilibrium and considers the fishing mortality (F) which corresponds to the tipping point of the maximum yield as F_{MSY} (Marta Coll and Jeoren Steenbeek, pers. comm.).

Model Validation

To assess model skill, a quantification of the misfit between model results and observations needs to be performed (Jolliff et al., 2009). Many studies have demonstrated the importance of using a suite of metrics for model validation, e.g., Saux Picart et al. (2012). Use of multiple metrics both aids the identification of differences between the model-generated data and available observations, and provides insight into the cause of the differences. In this study a suite of univariate (e.g., Jolliff et al., 2009; Stow et al., 2009) metrics including RMSE (root mean square error), bias, unbiased RMSE, and Pearson Correlation Coefficient were used to assess the skill of and benchmark model outputs. The variables compared against data are Temperature (T), Salinity (S) as well as concentrations of nitrate (NO_3), dissolved oxygen (DO), hydrogen sulfide (H2S), ammonia (NH4), Phosphare (PO4), and Chlorophyll-a (CHL).

Observational data used to validate the circulation and biogeochemical models were compiled from all available data obtained from the Black Sea database (produced following the NATO SfP ODBMS project; http://sfp1.ims.metu.edu.tr). The relative performance of the simulation in reproducing observed parameters are summarized using Taylor (2001) and Target diagrams. Simulated circulation fields are additionally compared qualitatively to satellite derived observations using the AVISO+ (*Archiving, Validation, and Interpretation of Satellite Oceanographic data)* Sea Level Anomalies (SLA) regional product for the Black Sea. (http://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/regional/msla-black-sea.html). The mean sea surface height provided by Korotaev et al. (2003) was added to the AVISO fields to compute the absolute dynamic height (ADT) of the Black Sea. ADT was then used to compute the geostrophic currents that were compared to model surface currents.

One way to validate the biogeochemical model is to compare model chlorophyll *a* concentrations with available satellite data. To do so chlorophyll data was obtained from the European Service for Ocean Color (GlobColor) Global product (http://globcolour.info), which includes reprocessed Level 3 data from satellites MERIS, MODIS AQUA, SeaWIFS, and VIIRS for the period 1998–2014. Of the different satellite data used to create this product the MERIS data was produced using the OC4Me algorithm, SeaWIFS data was produced with the OC4v5 algorithm, and the MODIS/VIIRS data were produced using the OC3v5 algorithm. The GlobColor data set consists of daily maps of near-surface chlorophyll *a* concentration (mg m^3) with a 4-km resolution and data has been developed, validated, and distributed by ACRI-ST, France. For validating the biogeochemical model this satellite data set is the best available, however it should be noted that there are errors already associated with this data set. The OC algorithms used in this product have been developed for case 1 waters, which are bodies of water whose optical properties are mainly influenced by phytoplankton and related colored dissolved organic matter (CDOM) and detritus degradation products and often tend to be waters further offshore. The Black Sea however, is mainly composed of case 2 water, i.e., coastal waters influenced strongly by inorganic substances and CDOM whose concentrations do not covary with the phytoplankton concentration (Gordon and Morel, 1983). Hence, these algorithms overestimate chlorophyll concentrations in the Black Sea (Gregg and Casey, 2004; Sancak et al., 2005; Zibordi et al., 2013). Gregg and Casey (2004) document a positive bias of 44% across the entire range of chlorophyll observed and especially at low concentrations. This overestimation is thought to be mainly due to yellow substance or colored dissolved organic matter (CDOM) (Burenkov et al., 2000). In addition, Cokacar et al. (2001) found high reflectance in the Black Sea due to coccoliths that also may be causing overestimation. In addition, when calculating time-averages of % errors between the different satellite data sets used to compile this chlorophyll product (not shown here) this error is between 100 and 120% in the entire Black Sea basin. Only the northwestern shelf region, where satellite algorithms traditionally do poorly due to high CDOM concentrations from riverine input, displays errors below 100%, indicating all algorithms have similar difficulties detecting chlorophyll in this region. Therefore, when comparing model results with satellite data this high error associated with satellite observations should be kept in mind.

The HTL model validation of fish stocks was carried out by comparing model results with XSA estimates for biomass and catch statistics for model catch (STECF-15-16, 2015) using a suite of univariate (e.g., Jolliff et al., 2009; Stow et al., 2009) metrics similar to the physical model validation. Although, XSA is the most widely used single-species stock assessment method, it is tightly coupled to catch statistics and assumes that catch and catch-at-age data are fixed. Biomass is estimated based on this and the presence of a tuning index, whose value is assumed to be proportional to biomass at sea. This method includes uncertainties (Shepherd, 1999) also it excludes explicit trophic interactions and summarizes all the food web-related processes in one single empirically calculated term, natural mortality. Mechanistic trophic models however, such as EwE used in this study, include explicit representations of prey-predator interactions in the food web. Beyond that, statistically the fit of the model to the data were assessed using sum of squared deviations (SS) of log estimates of biomass and catches against the log data of biomass and catches of fish species and Akaike Information Criterion (AIC).

Considering that the EwE model was used to produce F_{MSY} estimates, which the management advice from this study is based on, a Monte-Carlo type parameter search routine was carried out for the base Ecopath model parameters. The initial parameters of the Ecopath model (i.e., production per unit of biomass and production per unit of consumption) were ranged within a given coefficient of variation (10%) and the Ecosim model for the hindcast period (2000–2014) was run and its output was compared against the biogeochemical model outputs as well as XSA and catch statistics data to obtain better values for the parameters. This approach provided a better fit for the dynamic Ecosim model to the reference data, hence, addressing some uncertainty due to our parameterization. The final values used for simulations are given in Table S1.

In addition, as discussed in section Changes in Ecosystem Structure and Fish Stocks under Future Climate Scenarios we provided uncertainty ranges of our estimates. To obtain the given ranges, we carried out the F_{MSY} estimation routine for each year in the whole simulation period by utilizing each year's corresponding fisheries exploitation and biomass levels (21 F_{MSY} values for 21 years). This helped us to calculate what would have been the optimum fisheries exploitation level if each year's stock and fisheries exploitation levels had been considered. The optimum fisheries exploitation levels were calculated separately for each year's stock and fisheries exploitation levels. Assuming that the future stocks' progressions fluctuates within their corresponding historical ranges, the ranges given in section Changes in Ecosystem Structure and Fish Stocks under Future Climate Scenarios provide the uncertainty of our F_{MSY} estimates.

RESULTS

Assessment of the Current Status

The Black Sea is characterized by a basin-wide cyclonic gyre, with an intense, narrow rim current flowing along the shelf edge and a number of anticyclonic eddies along the coast (Oguz et al., 1993; Korotaev et al., 2003; Zatsepin et al., 2003). The circulation structure is predominantly driven by wind stress curl and modulated by seasonal evolution of the surface thermohaline fluxes (Kubryakov et al., 2016). The physical model correctly predicts the overall circulation characteristics of the Black Sea (**Figure 4**). The modeled rim current flows cyclonically along the steep bottom topography of the continental slope as expected, but is slightly faster in speed than the rim current derived from satellite data and there is a discrepancy between model and observations in the area east of the Crimean Peninsula where the model predicts currents that turn north after passing the peninsula instead of continuing directly west. Furthermore, on the northwestern shelf, model deviates from the observed flow on the northern part of the shelf where the modeled currents flow northward and eastward near the northwestern cost instead of flowing south and west as in the satellite derived fields. This was found to be due to the discrepancy between the observed and modeled wind fields in the area and leads to model uncertainty in the northwestern shelf.

Models skill is best for the physical variables, T and S and also for oxygen (**Figures 5A,B**). The presence of oxygen is a crucial factor in determining the biogeochemical reactions that take place within the Black Sea, and therefore it is important that the model is able to predict oxygen and hydrogen sulfide concentrations relative accurately. Phosphate and ammonium correlate better with the data compared to nitrate; the bias of modeled nitrate is higher (**Figures 5A,B**). Comparison of chl-a concentrations with satellite data shows that the model is able to reproduce the seasonal bloom dynamics in the Black Sea (not shown here) with low chlorophyll concentrations during summer, the phytoplankton bloom starting in fall (September–October) and continuously high chlorophyll concentrations during winter (Nezlin, 2006; McQuatters-Gollop et al., 2008). Concentrations decrease again in winter with the onset of stratification. The difference in chlorophyll concentration between model and satellite observations (**Figure 6**) shows regional differences in model skill. The two open sea regions 4 and 5 show a good fit with observations indicating high model skill, whereas in the coastal regions of the Black Sea uncertainty increases (**Figure 6**). Highest discrepancy is found in the coastal

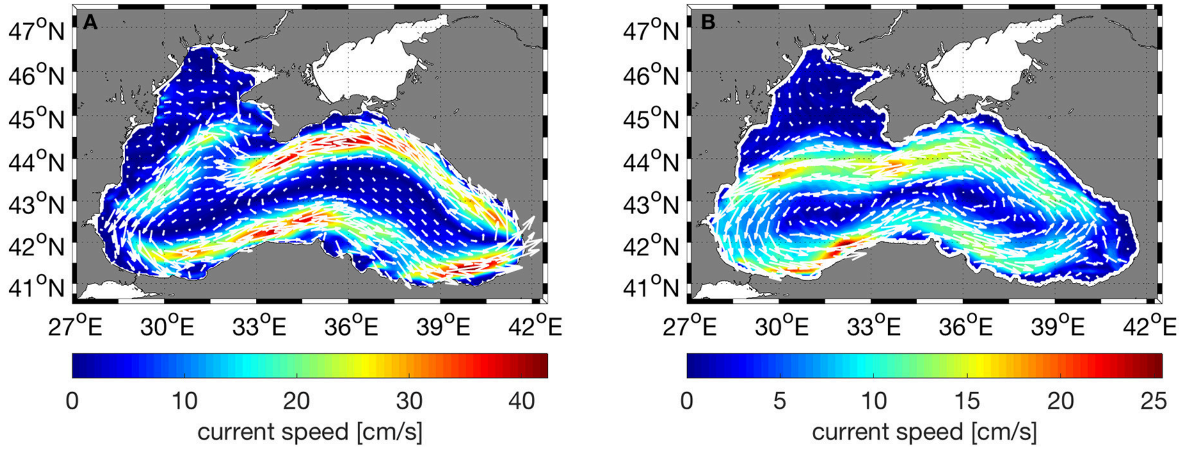

FIGURE 4 | Comparison of **(A)** model surface currents (cm/s) with **(B)** geostrophic currents (cm/s) computed from satellite derived absolute dynamic topography. In both plots, the currents were time averaged for 5 years (2010–2014).

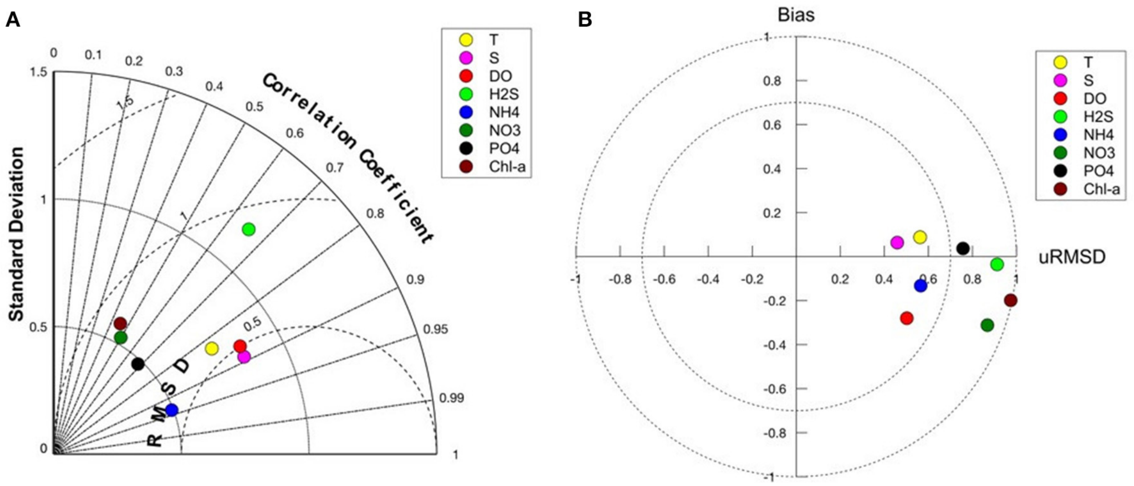

FIGURE 5 | (A) Taylor diagram showing model-data comparison of the lower trophic level model hindcast simulation with data obtained from the Black Sea data base (http://sfp1.ims.metu.edu.tr). The angle describes the correlation between model and data, the distance from the origin is the normalized standard deviation and the dashed circles around reference point (1) on the x-axis defines the root mean squared error. **(B)** Target diagram of model-data comparison. The y-axis corresponds to the normalized bias, the x-axis corresponds to the unbiased RMSD (root mean square deviation).

areas of the northwestern shelf specifically along the Danube river mouth, which corresponds to region 3 in this study. Part of this large error is due to satellite estimations of chlorophyll grossly overestimating chlorophyll concentrations in coastal regions (Oguz and Ediger, 2006). This is especially the case for the Black Sea, given the algorithms used in the GlobColor data product. However, in part this error is due to model circulation on the northwestern shelf which is not moving cyclonically as observed but rather water is transported northeastward, reducing production levels at the western coast. Model misfit in region 1 is rather low, the model produces slightly less chlorophyll than observed. While in region 2, close to the northeastern Black Sea coast the chlorophyll values are overestimated by the model. Similar misfits are common among Black Sea models because of the complexity in the circulation and biogeochemical dynamics of the Black Sea (Korotaev et al., 2011; Miladinova et al., 2016).

Modeled biomass values of fish generally show good fit with the data (**Figure 7**). Apart from catches of sprat and predatory fishes; bluefish, bonito and Atlantic mackerel, the HTL model-estimated catch values also show good model skill (**Figure 7**). Considering sprat, the highest deviations (SS ∼ 20) come from fits of sprat catches, for which the XSA biomass estimates were high but catch values reported were low compared to the predicted biomass and the fishing mortality estimates from XSA analysis. This suggests that the catches could possibly be much higher than the reported amount, or that the XSA biomass and fishing mortality estimates include high uncertainties. The same may be suggested for anchovy as well. Illegal, unreported and

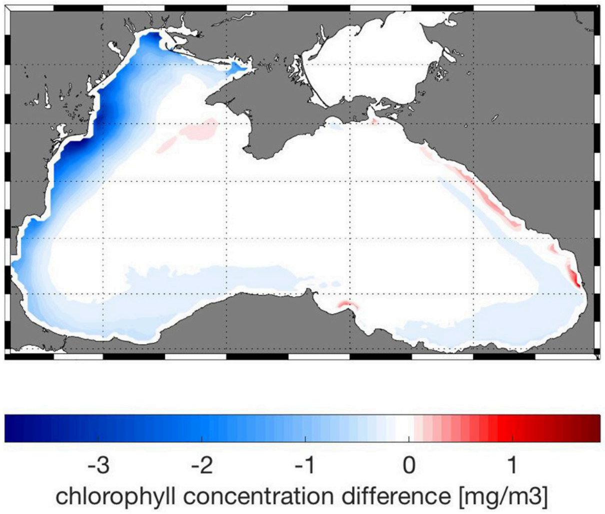

FIGURE 6 | Absolute difference between model and satellite chlorophyll concentrations averaged over 5 years (2010–2014) in mg/m3.

unregulated (IUU) catch is a common practice in the Black Sea especially for the Turkish fishing fleet, which constitutes the majority of the fishing effort and the catches in the Black Sea. Particularly for small pelagic fish such as sprat and anchovy, IUU catches were shown to be very high (Ulman et al., 2013). Hence, the model simulated catches can be considered to be comparatively more realistic than what is reported by fisheries statistics.

Predatory fish do not have estimated fishing mortality values, therefore the fishing mortality values calculated for the initial conditions of the model (i.e., of year 2000) were used as constant throughout the hindcast simulation period (2000–2014). Hence, the deviations of model results from the catch values given in STECF-15-16 (2015) for these fish are the main reasons of the total deviation scores calculated for the hindcast scenario (SS $\sim$ 14 for Bluefish catches, SS $\sim$ 14 for Bonito catches and SS $\sim$ 82 for Atlantic mackerel catches). Apart from the catches of these four fish species, the model skill was high (SS = 305, AIC score = 103, against 408 AIC points).

In addition, the statistical properties of the model simulation given in **Figure 8** showed uncertainty of simulation results of different groups in reproducing the XSA estimates and catch statistics. The simulation results of biomass and catches of turbot, whiting and dogfish show better confidence in correlation values compared to other groups (**Figure 8**). However, although other groups had low correlation values with the compared data, the RMSE and bias values were comparatively low (RMSE slightly above 1 and bias of about 10–20%) for the majority of the groups except for horse mackerel and turbot catches, and whiting biomass and catches.

Changes in Ecosystem Structure and Fish Stocks under Future Climate Scenarios

The temporal evolution of net primary production anomalies in the five regions defined in this study (**Figure 9A**) show great variability in production between different regions and years, as well as seasonal variability. Region 3, the northwestern shelf region, shows the largest range in anomalies followed by the two inner basin regions 4 and 5. All net primary production anomalies are mainly negative after 2014 with region 3 again being the most extreme case with the highest variability (**Figure 9A**). All regions show the same general trend in anomalies during the future simulation and that is a slight increase until 2017, a sudden drop in 2018 and increase in anomalies thereafter.

Mesozooplankton biomass variability in the five regions (**Figure 9B**), which is considered as the main food source for small pelagic fish, also show that region 3, the northwestern shelf has the largest range, followed by the other coastal regions 1 and 2. The strong variability of net primary production in region 3 translates into mesozooplankton as well, as expected. All regions show the same general trend in mesozooplankton biomass during the future simulation and that is a slight increase until 2017, a sudden drop in 2018 and increase thereafter. Differently, mesozooplankton biomass in regions 3, 4, and 5 decrease from 2014 to 2018 and only increase in 2019.

Net primary production (NPP) shows an overall decrease in all regions for the future period (**Table 1**). Much of the reduction in NPP is along the western coast of the Black Sea, the central basin and also along the northeastern coast (**Figure 10A**). At the same time, future NPP increases in the northern part of the northwestern shelf and to a rather small extent in the western central gyre. Lowest overall reduction occurs in the western gyre of the basin, region 4 (**Figure 10A**, **Table 1**). Zooplankton biomass (**Table 2**) follows this reduction in primary production although the magnitude of decrease is more pronounced (22 vs. 10%). The spatial pattern of increase and decrease of zooplankton follows that of net primary production (**Figure 10B**) as can be expected. Strongest increase in biomass occurred on the northern-central northwestern basin, while a decrease occurred at the very northern part. Strongest decrease was in a wide band along the western coast extending along the southern coast as well (**Figure 10B**).

Despite an average decrease in forecast averaged NPP values for the sub regions (**Table 1**), in general, most fish stocks are predicted to show an increase after 2018 (**Figure 11**). These increases are correlated to the NPP anomalies shown in **Figure 9A**. However, when the overall biomass of future stocks from 2015 to 2020 is compared with the past stock biomass (2000–2014), a decrease occurs for all the species except sprat. Our results show that when fishing mortality levels are kept at levels of 2014, stocks will gradually increase although the overall biomass will not exceed the past average levels. Sprat shows the highest relative increase (**Figure 11**) because of low fishing mortality rates during the future period.

Model results suggest that stocks of species such as horse mackerel, bonito and bluefish will continue decreasing (**Figure 11**) if current fisheries pressure is continued. This indicates that fishing mortality will have a stronger effect on these species than food web interactions (e.g., increase in anchovy and sprat biomass). Considering the sharp decrease of horse mackerel stocks, food web interactions come into play and

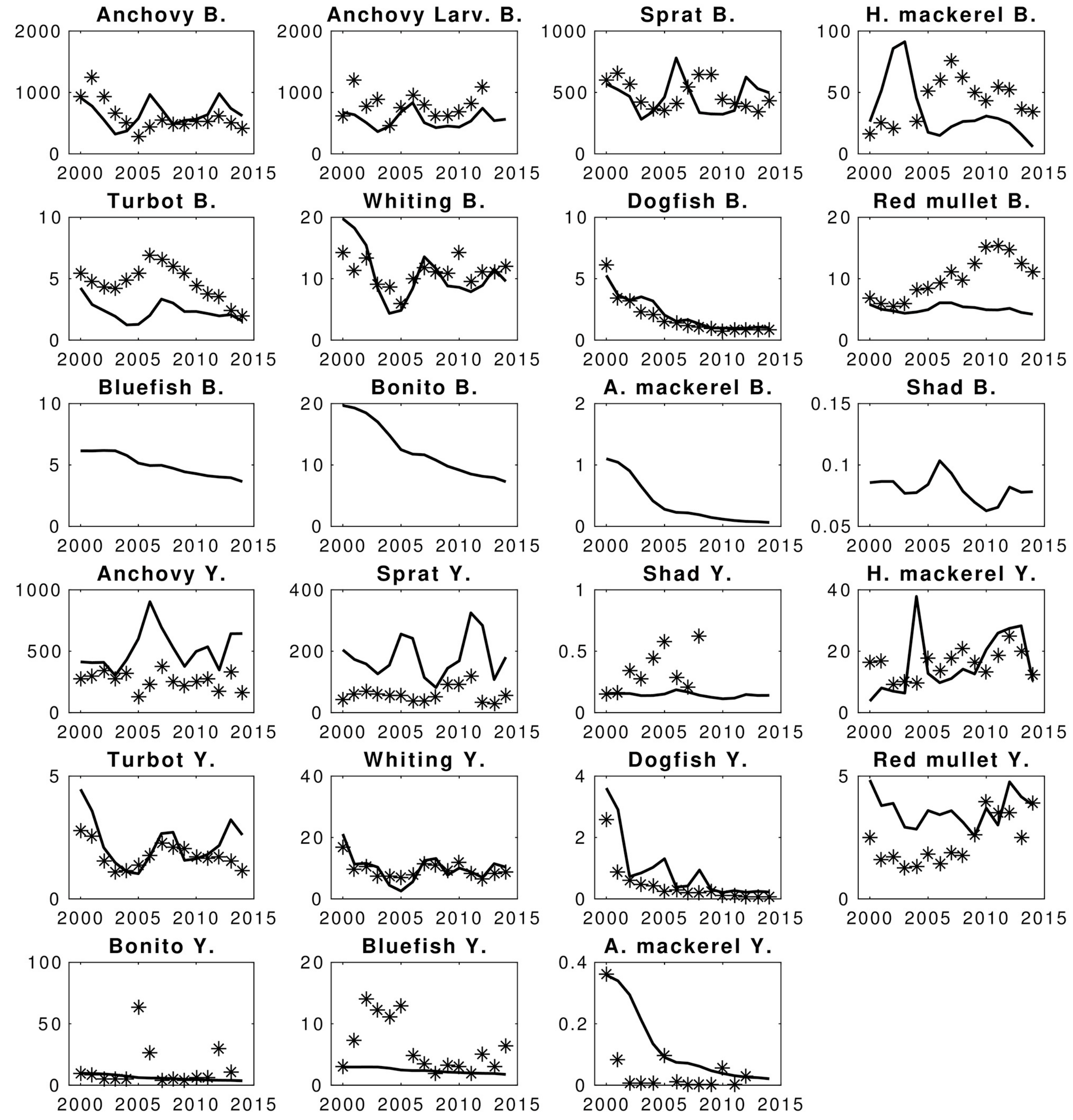

FIGURE 7 | Hindcast simulation results of the EwE fish model and fits to the statistical catches and conventional statistical stock assessment predictions. Stars denote the compared data and lines are the simulation results. X-axis denote years and Y-axis denote catches (Y.) and biomasses (B.) The units are in kilotons.

predation by whiting and turbot contributes to this decrease. Dogfish also shows a continuous decrease despite lower fishing mortality values, caused indirectly by high by-catch. Increase in anchovy biomass during 2018–2020 (**Figure 11**) will not be sufficient to start a recovery of dogfish stocks as well as horse mackerel because from a trophic perspective, whiting and turbot outcompete these two species in exploiting the resources. This is due to the long life-cycle (low P/B in the model) of dogfish and its high by-catch (BSC, 2008).

Modeled fish biomass shows distinctive differences across regions although the initial fish biomass and fisheries pressure were assumed to be homogenously distributed. In the future in all regions fish biomass is expected to show a high fractional decrease compared to present levels other than sprat and, to

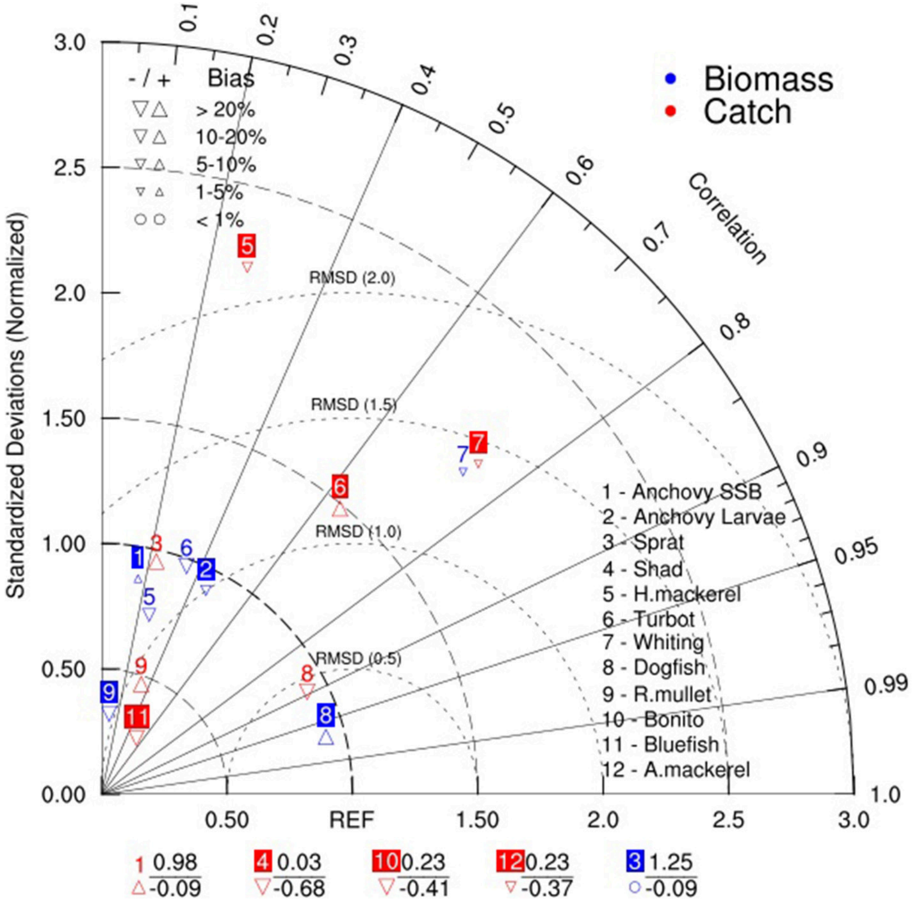

FIGURE 8 | Taylor diagram showing comparison of the higher trophic level model hindcast simulation with data obtained from STECF-15-16 (2015). The angle describes the correlation between model and data, the distance from the origin is the normalized standard deviation and the dashed semi-circles around reference point (REF) on the x-axis define the root mean squared error/distance (RMSD). The labels at the bottom of the figure show summary statistics of groups with negative correlations (below) and their respective normalized standard deviations.

an extent, anchovy (**Figure 12A**). However, these small factional changes in anchovy and sprat translate into a high biomass change (**Figure 12B**). Sprat and anchovy in region 3 are the only stocks expected to increase in the future. Small species (i.e., anchovy and sprat) and red mullet stop their decline and start an increase after 2017 whereas larger species (e.g., Atlantic mackerel and horse mackerel, whiting, bluefish, bonito) continue to decrease in all regions until the end of 2020 (**Figure 11**). Biomass of these species are highest in region 1 followed by region 3 which experience the highest NPP and zooplankton levels (**Figures 9A,B**). Results show that sprat is the only species that may show an overall increase in the future (**Figure 11**), if 2014 fish mortality values (cf. section Assessment of Fishing Mortality Rates) are maintained.

Assessment of Fishing Mortality Rates

Fisheries mortality rates for the years 2000 to 2014 (**Figure 13**) indicate all stocks were exploited above their sustainable levels. Exploitation rates were close to 1 for most stocks; especially high for anchovy, horse mackerel, turbot, whiting, red mullet, shad, bonito, bluefish, and Atlantic mackerel. Model-based F_{MSY} values for anchovy and red mullet are close to the STECF estimations although STECF estimates may include high uncertainties (STECF-15-16, 2015). These uncertainties stem from the single-species stock assessment method, XSA used by STECF which ignore explicit trophic interactions in the food web. However, they still represent the best catch data-based values available. On the other hand, model-based estimates for sprat, dogfish, whiting and turbot catch were lower compared to the STECF values.

DISCUSSION

The observed decrease in NPP in the biochemical model is in agreement with other modeling studies using future climate change scenarios such as the comparison of four different global models that predict lower net primary production rates for future (2012–2100) climate under IPCC's emission scenario RCP8.5 (Laufkötter et al., 2015, 2016). Several other studies of the global ocean projected global marine net primary

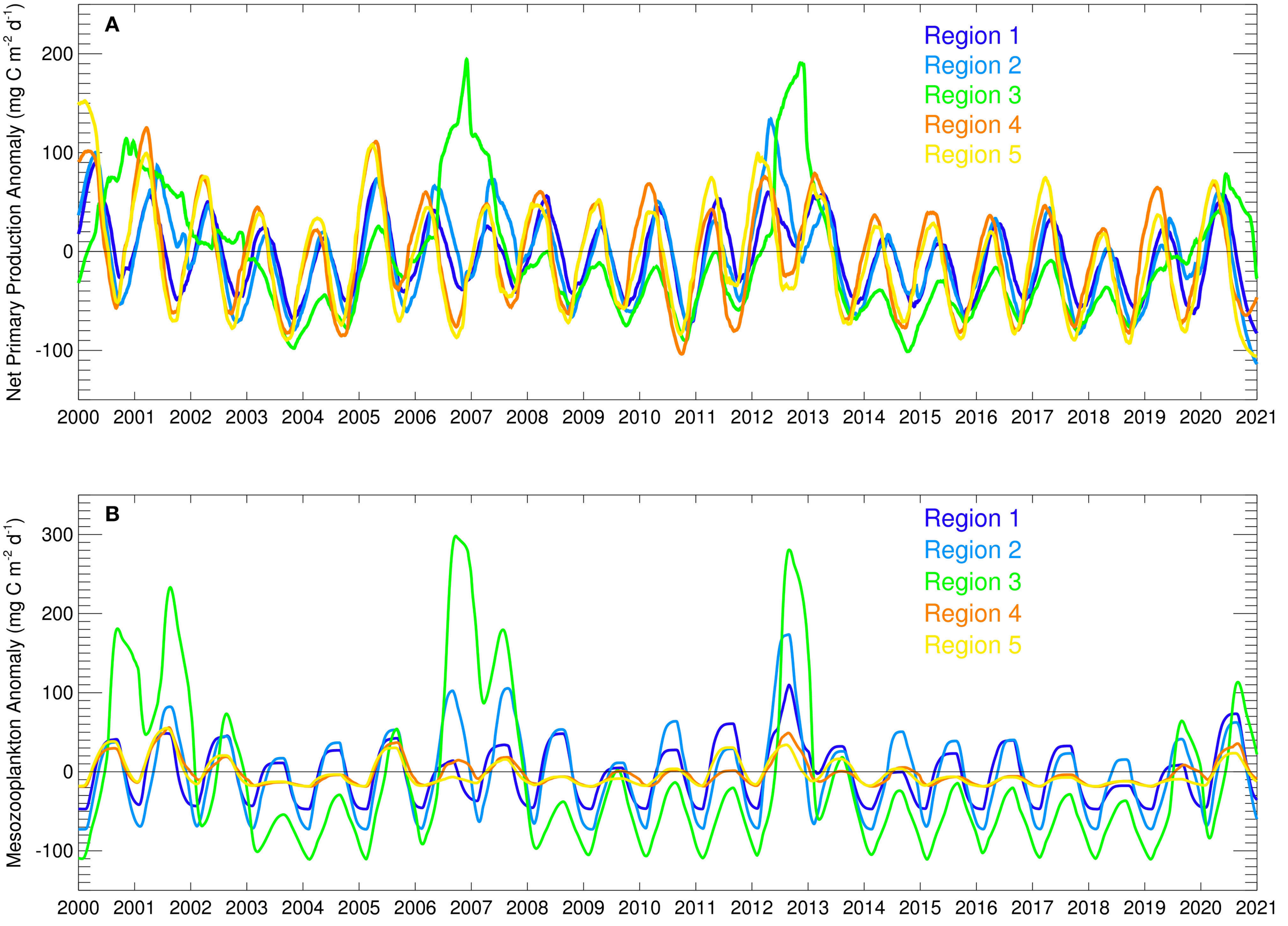

FIGURE 9 | Time series of modeled **(A)** net primary production anomalies (mg C m^{-2} d^{-1}) and **(B)** mesozooplankton biomass anomalies (mg C m^{-2} d^{-1}) in the five different regions.

production to decrease in response to future climate change (Bopp et al., 2001, 2013; Boyd and Doney, 2002; Steinacher et al., 2010; Marinov et al., 2013; Cabré et al., 2014). The main mechanism that has been suggested to explain such decrease was increased stratification of the water column and hence reduced supply of nutrients to the surface layer (Bopp et al., 2001; Steinacher et al., 2010). The reduced nutrient availability caused decreased phytoplankton growth and therefore reduced net primary production. In addition, increased grazing pressure caused by warmer water temperatures may be of importance of reduced net primary production as well (Laufkötter et al., 2015). A similar reduction in production has been observed and predicted for future climate in the Indian Ocean (Roxy et al., 2016). It is important to note that most of these predictions show spatial variations in net primary production increases and decreases over the area investigated, which also occurred in the current study. Holt et al. (2016) show spatial variations of net primary production for a far future simulation (2100) for different European Seas which amount to a net decrease in production only for the northeast Atlantic, contradicting our finding for the immediate near future.

TABLE 1 | Regional fractional changes in biogeochemical model variables between periods 2010–2014 and 2015–2020 in different regions.

	Basin	Region 1	Region 2	Region 3	Region 4	Region5
NPP	−0.10	−0.11	−0.09	−0.10	−0.05	−0.11
Zooplankton	−0.22	−0.20	−0.19	−0.16	−0.11	−0.24

The Black Sea ecosystem function is regulated by bottom-up controls since the onset of 1970s (Daskalov, 2002; Gucu, 2002; Oguz, 2007; Akoglu et al., 2014). This regulation mechanism was also observed in the hindcast simulation of this study. Small pelagic fish stocks; i.e. anchovy and sprat, are influenced by the changes in the primary productivity (**Figures 7**, **9A**). This direct effect of NPP is also known to occur for small pelagic fish on a global scale (Blanchard et al., 2012). In years when net primary productivity was higher than the long-term average (years 2005–2007 and 2011–2013) increases in the respective small pelagic fish stocks were observed. The modeled sprat stock changes matched the peak observed in 2005 as reported in BSC (2008). A similar peak was also simulated

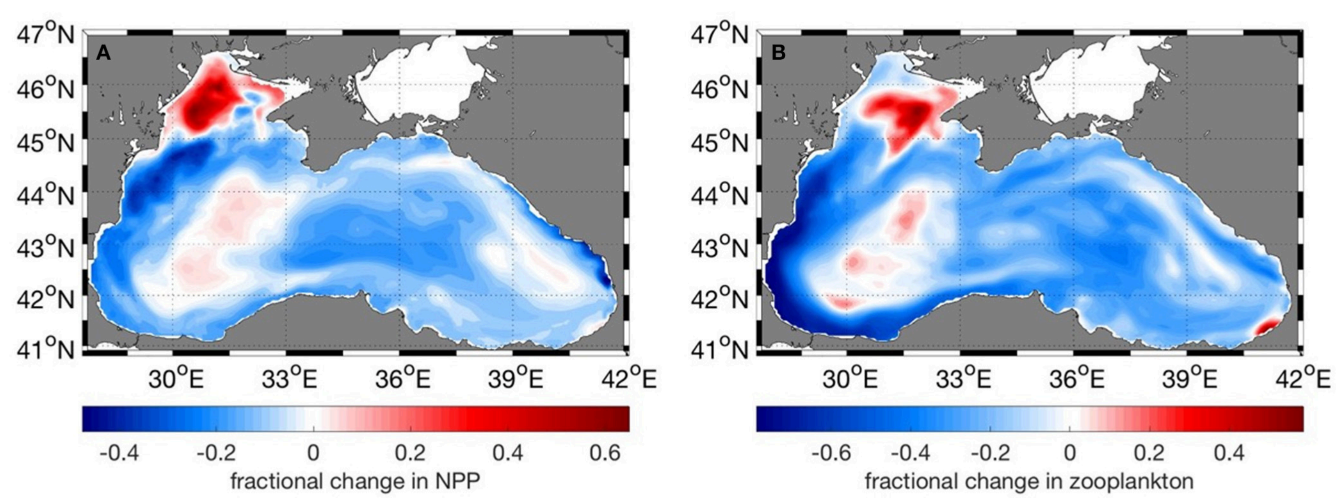

FIGURE 10 | Fractional change of **(A)** Net Primary Productivity, **(B)** Zooplankton biomass between the present (2010–2014) and future (2015–2020) periods. Negative values mean a decrease in the years 2015–2020.

TABLE 2 | Model predictions of fishing mortality (F_{MSY}) and maximum sustainable yield (MSY) for sustainable fisheries exploitation of fish groups in the Black Sea and their comparison to the F_{MSY} values reported in STECF-15-16 (2015).

Species	F_{MSY} (this study)	F_{MSY} (STECF)	MSY (tons, this study)
Atlantic bonito	0.27	–	5,317
Bluefish	0.26	–	1,599
Atlantic mackerel	0.03	–	33
Whiting	0.25	0.79	4,941
Turbot	0.49	0.26	1,136
Red mullet	0.52	0.64	2,638
Spiny dogfish	–	–	–
Horse mackerel	0.34	–	8,910
Shad	0.44	–	37
Sprat	0.32	0.64	148,518
Anchovy Ad.	0.41	0.49	267,459

for anchovy stocks, leading to a very high simulated catch for the years 2005 and 2006. Excluding these high production periods, small pelagic fish stocks declined under the impact of status quo fisheries exploitation, which has been classified to be "intense" by many authors (Daskalov, 2002; Oguz, 2007; Llope et al., 2011). Such increases in system NPP act as a mitigating factor for the overexploited small pelagic fish stocks without which they would collapse under conditions of continuous overexploitation. Similarly, simulated predators of small pelagic fish stocks, e.g., whiting and turbot, also benefited from the respective increases in their prey despite heavy fisheries pressure. However, this was not observed for simulated pelagic piscivorous fish, i.e., bluefish, Atlantic mackerel, and bonito, because of the extremely high exploitation rates they were exposed to and their longer life cycles (low P/B in the model).

Considering the steady decrease in stock of horse mackerel, a medium pelagic fish mainly feeding on zooplankton, anchovy and sprat, the observed and modeled dynamics were contrary to the ones observed in the stock increases of sprat and anchovy by 2020. This could partly be explained by the resource limitation for horse mackerel considering the high harvesting pressure of Black Sea fishing fleet on small pelagic fish whenever their respective stocks fluctuate for an increase so that not enough resources were left for horse mackerel. In addition, the other predators of small pelagic fish (i.e., whiting and turbot), which have been observed to fluctuate with the changes in small pelagic fish stocks, also predate on horse mackerel. The model shows a decrease in red mullet biomass, consistent with the high historical bottom trawling pressure red mullet stocks have been subjected to in the Black Sea, especially on the narrow continental shelf of the southern Black Sea (BSC, 2008). Dogfish is not directly targeted by fisheries; however, fishing mortality is caused by by-catch and this pressure was found to be high enough to cause a continued decrease in its stock.

During the forecast simulation, all regions showed an average decrease in NPP, however there was an increase in NPP and zooplankton during 2018–2020 after overall low values in the preceding years (**Figure 9**). Modeled anchovy results (**Figure 11**) mirror the impact of these changes in mesozooplankton biomass and their regional differences (**Figure 9**). For example, in region 3 anchovy showed the highest increase after 2017 in parallel to a high increase in mesozooplankton and in region 1 this increase started with a delay. These results show that the production, and thus climate, can affect anchovy stocks in similar magnitudes as fisheries pressure.

Species such as turbot and whiting, which feed on small species including anchovies and sprat, also suffer the effect of direct food web interactions. However, indirect interactions also have an effect in the form of resource competition with dogfish and horse mackerel. Compared to horse mackerel, which also

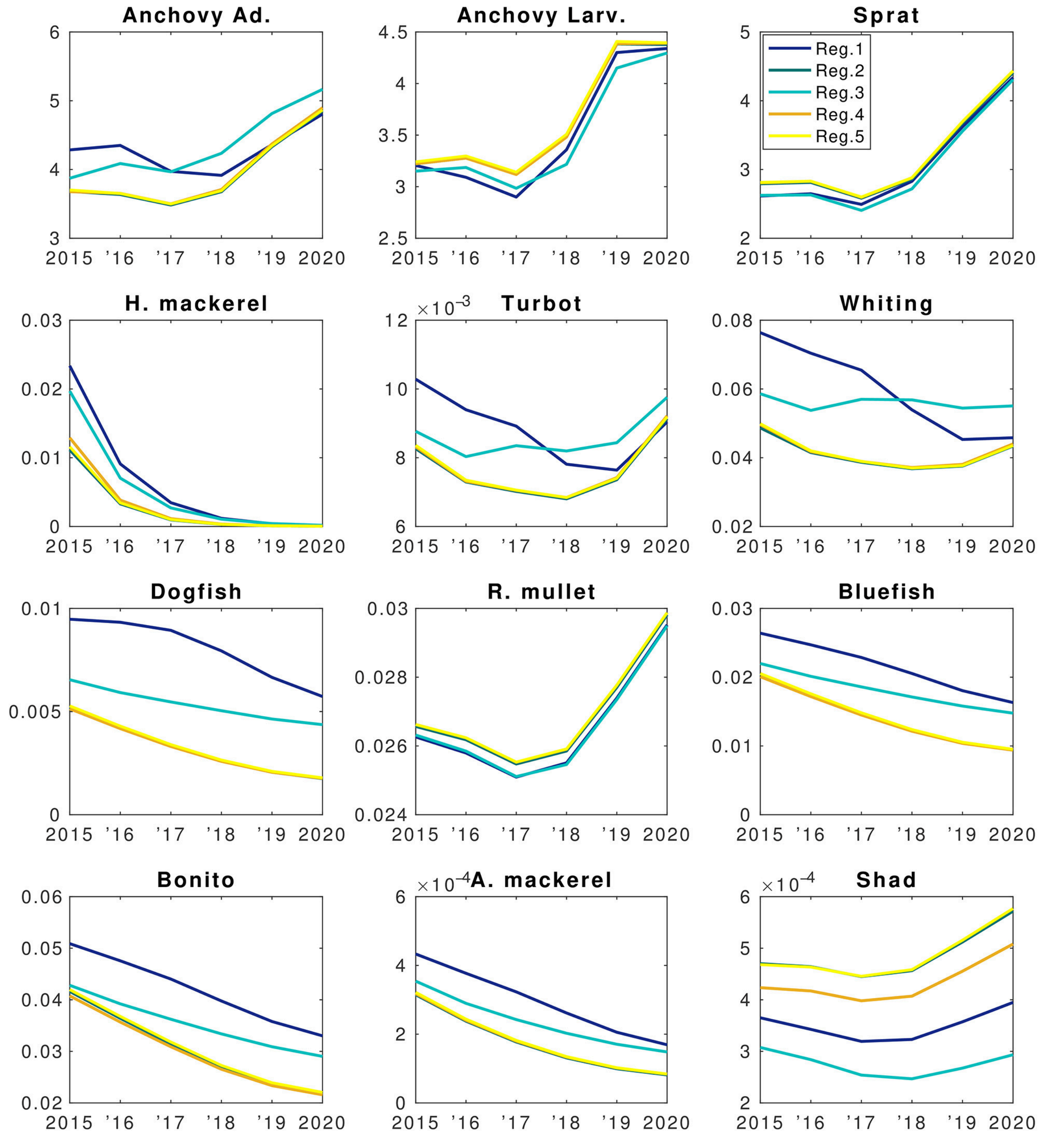

FIGURE 11 | Forecast simulation (2015–2020) results of the EwE fish model of the BAU scenario. X-axis denote years and Y-axis denote changes in biomasses (B.) The units are in tons km^{-2}. Colors denote different regions as explained in the top right panel.

occasionally feeds on anchovy and sprat, turbot and whiting have an advantage because in addition to sprat, they prey on horse mackerel as well. In the case of dogfish, its long life-cycle poses a significant disadvantage over its competitors. Their biomass continued to decrease after 2015 but an increase occurred in all regions during 2018–2020 due to an increase in their prey as a consequence of increased system-wide net primary production.

Larger species continued to decrease during the whole forecast period because of their extreme over-exploitation. Also, these species are limited by resources that prevent their stocks

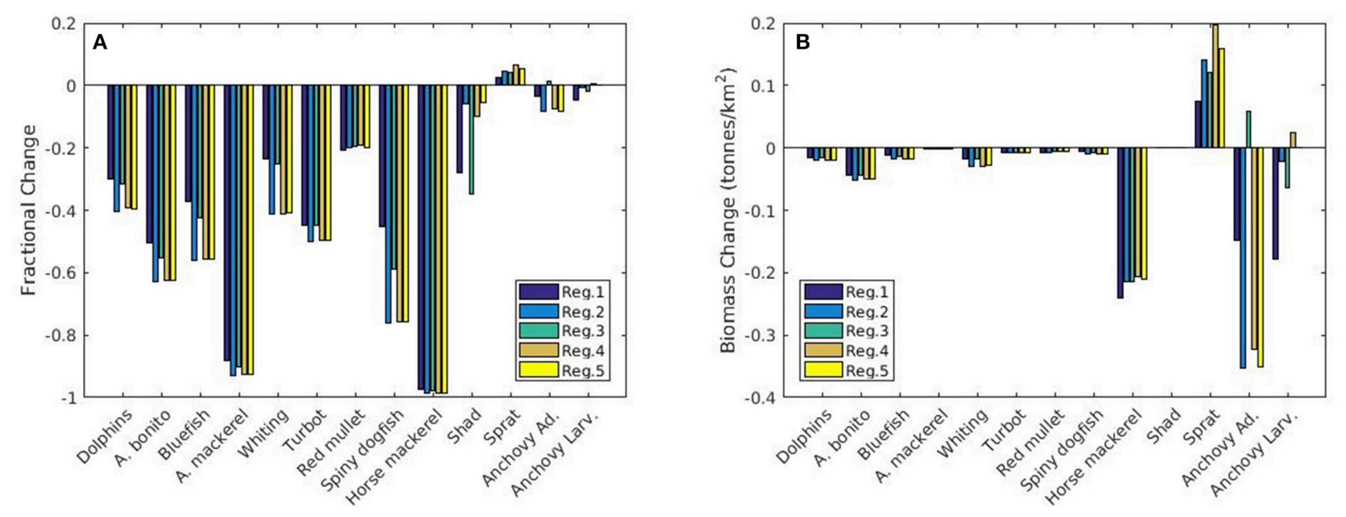

FIGURE 12 | (A) Fractional and **(B)** absolute change in biomass (tonnes km^{-2}) of different fish species for the five different regions of interest between the present (2010–2014) and future (2015–2020) periods. Negative values mean a decrease in biomass for the years 2015–2020.

from recovering. Any stock increase of small pelagic fish is immediately exploited by fisheries and very little is left to be utilized by piscivorous fish within the food web of the Black Sea ecosystem. Such indirect trophic impact of fisheries within the food web was also shown by Ulanowicz and Puccia (1990).

This study, for the first time, presents future stock size, F_{MSY} and MSY estimates for the Black Sea for 11 fish species (**Figure 13**, **Table 2**). In agreement with STECF-15-16 (2015), our results suggest that only sprat in the Black Sea is currently being exploited at a sustainable rate. Adjusting fishing effort to meet the F_{MSY} is generally problematic because it is difficult to determine the mortality created by a fleet with varying fishing time every season under the simultaneous fluctuations of stock size. Therefore, as a management strategy it is practical to define a maximum allowed catch limit, i.e., total allowable catches (TAC) or MSY, to control the fishing effort and the mortality that it imposes on the exploited stocks. In this study, we propose MSY values (**Table 2**) as basis for defining TAC limits for the fish stocks of the Black Sea. Excluding sprat, the estimates provided here are lower compared to the average catch over the hindcast period (2000–2014) underlining that the stocks have already been exploited above their sustainable levels (also as shown in **Figure 13**). We hypothesize that sprat stocks could be underexploited when biomass estimates from STECF-15-16 (2015) and this study are considered.

There are two potential reasons for mismatch in model versus STECF estimates (**Figure 7**). First, an important uncertainty in catch estimates is the IUU catches in the Black Sea as discussed (section Assessment of the Current Status). Second, we hypothesize that the disagreement stems from the incorporation of trophodynamics in calculations of the F_{MSY} estimates, which is absent in the single species based STECF estimates. Therefore, here we provide a range of F_{MSY} estimates. The lowest F_{MSY} values suggested here can be considered as a base in managing the Black Sea fish stocks and new estimations should be made as new data are obtained with every concluding fishing season, and finally carrying out a re-analysis with the complemented dataset to produce a strategy for the forthcoming fishing seasons. In addition to this strategy, improving the quality of the statistics collected by the Black Sea's non-EU riparian countries by strictly constraining the landings to designated areas where catch of each vessel is recorded and registered would help to decrease the uncertainty in the management strategies.

Another important consideration is the uncertainty in the results reported in this study. We have addressed the uncertainty in the inputs and parameters of the model as detailed in section Model Validation, as well as the uncertainty at each trophic level (section Assessment of the Current Status). Moreover, the merit of this study is that it provides a range of values by considering the uncertainty in the HTL model results for its management advice. A range of F_{MSY} values are provided by assuming that the historical fluctuations of the fish stocks observed in the hindcast scenario are the predictors of the intrinsic uncertainty in the forecast scenarios of the model and the ecosystem. Thus, we provide a range of suggested exploitation levels together with uncertainty levels of each fish stock estimations which has never done before in any fisheries management advice study in the Black Sea.

Fishing mortality estimates from XSA and multispecies trophic models are fundamentally based on the same information, the reported catch. But while XSA includes trophic relations in only one implicit term, the natural mortality, multispecies trophic models extend much beyond this and our model explicitly incorporates full trophic (predator-prey) interactions in the food web capitalizing on the literature data on diet and stomach contents. Our proposed F_{MSY} estimates (**Table 2**) are lower, and hence more conservative, than those proposed by STCEF-15-16 (2015), which is due to the differences in the approaches of two studies detailed above, among which the inclusion of trophic interactions in this study. This study

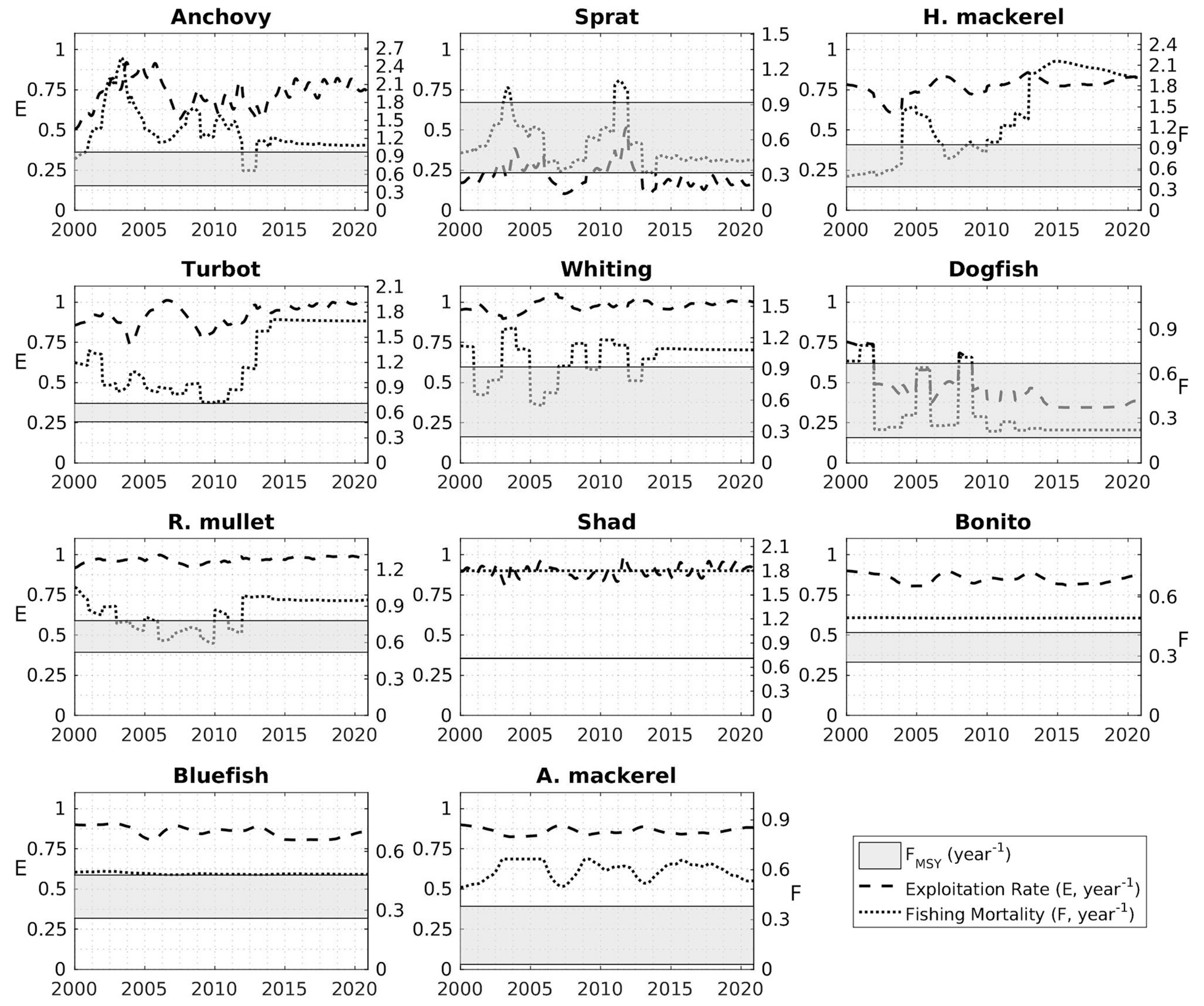

FIGURE 13 | Exploitation rates (E, dashed line) and fishing mortalities (F, dotted line) for the modeled fish groups during the hindcast (2000–2014) and forecast (2015–2020) simulation periods. The gray shaded areas denote the range bounded by the minimum and maximum values of F_{MSY} predicted by the model.

also provides F_{MSY} and MSY estimates for the stocks of pelagic piscivorous fish; bonito, bluefish and Atlantic mackerel, for which these estimates have never been scientifically developed. Managers should be provided with evidence-based information showing the need to sustain sufficient prey fish in the ecosystem in order to support the dynamics of charismatic (i.e., predatory) fish species of their particular marine ecosystem considering indirect trophic impacts of fisheries within the food web (Akoglu et al., 2014 for the Black Sea and Ulanowicz and Puccia, 1990 for theoretic background). Otherwise, an ecosystem-wide collapse as previously experienced in the Black Sea (Oguz et al., 2012) is inevitable. Our proposed management criteria will allow the recovery of these fish species of the Black Sea, i.e., bluefish, bonito, and mackerel, in addition to ensuring the sustainable utilization of other fish stocks in the long-term.

Total allowable catches or fishing opportunities, are catch limits that are set for most commercial fish stocks. At present, the Black Sea is missing multi-annual plans for setting basin-wide TACs. There are examples from other regions of how models such as Ecopath with Ecosim are used to evaluate TACs across multiple species by being utilized as management strategy evaluation tools (Grüss et al., 2016 and references therein). There are also other advances in food web models for marine systems for guiding fisheries management (Smith et al., 2011, 2015; Shin et al., 2012). Our work adds on to these efforts by proposing TAC values until 2020 based on an integrated circulation-biogeochemical model that includes the effect of environmental and climate variations.

Even though our model includes species interactions together with the effect of environmental and climate variability, results include uncertainties based on the included model forcing and assumptions in model structure as well as parameterization (see section Model Validation). Ecosystem models are very useful tools for fisheries management, especially in presenting the ecosystem under given conditions and for scenario testing, however, their results should be viewed and used considering the uncertainties.

CONCLUSIONS

This study presents the evolution of Black Sea fish stocks under changing trophic, environmental, and climate conditions both for the past 15 years and projects these estimates until 2020. Here we show the effect of primary production and secondary production versus fisheries pressure in regulating the fish stocks. Results show that changes in planktonic production have a direct effect on small pelagic fish even under the high fisheries pressure. For example, anchovy and sprat stocks are directly influenced by the fluctuations in net primary productivity. During years of higher-than-average NPP, these stocks increase even under high fisheries exploitation levels realized during the hindcast period. On the contrary during years of average or lower-than-average NPP, these stocks decline indicating their fragility. Hence, management advice should be developed considering both the productivity of the system and the fisheries exploitation levels, otherwise, unexpected collapse of these stocks might be experienced. The modeling approach used in this study, where a biogeochemical model was integrated with an HTL model, is a novel way of delivering such management advice.

This modeling study shows how a combination of fisheries, climate and food web interactions can act to regulate the fish stocks. Results have strong implications both at a regional and global scale. For long-term sustainability, exploitation levels should be reduced significantly for all species but especially for the piscivorous fish (i.e., bluefish, bonito, and Atlantic mackerel) as well as for anchovy, a species that plays a crucial role in supporting the food web as a forage fish. Short-term fisheries losses may be compensated by higher exploitation of the sprat stock compared to anchovy. In the long-term, we hypothesize that the management strategy proposed in this study will have a significant return toward sustainable utilization of Black Sea fish stocks under changing environmental and climatic conditions. And the most significant pay-off can be the recovery of predatory fish stocks and its fishery which has ever been inefficient since the onset of the 1970s after the overexploitation of these fishes during 1950s and 1960s.

The effect of gelatinous carnivores is implicitly included in the model by defining the jellyfish group in the HTL model according to the simulation outputs of the biochemical models' gelatinous carnivore compartment. A fully (two-way) coupled model would allow an assessment of direct and indirect competition between the gelatinous and fish species. Also models that include feeding and migratory behavior of fish are needed to better assess the regional differences and to provide management options at a regional scale in the Black Sea. At the moment, regional quantification that we provide includes only regional environmental and climate impacts whereas differences in fish stocks due to migratory behavior are neglected. Efforts to develop fully coupled models of biogeochemistry and food web are underway (e.g., Akoglu et al., 2015; Disa, 2016) as well as fish models that include behavior (e.g., Cowen and Sponaugle, 2009; Xu et al., 2013; Guraslan et al., 2017). However, the modeling community is limited by dependable observations. Reliable data on zooplankton levels as well as fish stocks and catch is crucial to reduce the uncertainty of integrated models that can be used to produce management options.

AUTHOR CONTRIBUTIONS

BS conceived and designed the research. SA, BF, and EA designed and implemented the model. All authors analyzed model results and contributed significantly to the writing of the paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2017.00339/full#supplementary-material

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Critical Inconsistencies in Early Implementations of the Marine Strategy Framework Directive and Common Fisheries Policy Objectives Hamper Policy Synergies in Fostering the Sustainable Exploitation of Mediterranean Fisheries Resources

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The Marine Strategy Framework Directive (MSFD) aims to achieve “Good Environmental Status” (GES) in EU marine waters by 2020. This initiative started its first phase of implementation in 2012, when each member state defined the GES and environmental targets in relation to 11 descriptors and related indicators for 2020. In 2013, the EU Commission launched the reformed Common Fisheries Policy (CFP), which aims to achieve biomass levels capable of producing maximum sustainable yield (MSY) for all commercial stocks exploited in EU waters by 2020, as well as contribute to the achievement of GES. These two pieces of legislation are aligned since according to Descriptor 3 (commercial fish and shellfish), the MSFD requires reaching a healthy stock status with fishing mortality (F) and spawning stock biomass (SSB) compatible with the respective MSY reference limits for all commercial species by 2020. We investigated whether the two policies are effectively aligned in the Mediterranean Sea, an ecosystem where the vast majority of stocks show unsustainable exploitation. For this purpose, we assessed and compared the number and typology of stocks considered by the member states when assessing GES in relation to data on stocks potentially available according to the EU Data Collection Framework (DCF) and the proportion of landings they represented. The number of stocks considered by the member states per assessment area was uneven, ranging between 7 and 43, while the share of landings corresponding to the selected stocks ranged from 23 to 95%. A lack of coherence between GES definitions among the member states was also revealed, and environmental targets were less ambitious than MSFD and CFP requirements. This could possibly reduce the likelihood of achieving fishery sustainability in the Mediterranean by 2020. These conditions limited the envisaged synergies between the two policies and are discussed in consideration of the recent Commission Decision on criteria and methodological standards for GES.

Keywords: Marine Strategy Framework Directive, Common Fisheries Policy, Good Environmental Status, Data Collection Framework, Data Collection Regional Framework, stock assessment

INTRODUCTION

In 2008, the European Commission approved the Marine Strategy Framework Directive (Directive 2008/56/EC; MSFD; EU-COM, 2008), which was the new legislation put forward under the coordination of the EU Directorate-General for Environment aimed at achieving "Good Environmental Status" (GES) in EU waters by 2020. This concept represents "the environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy, and productive" (Article 3; EU-COM, 2008). According to the MSFD implementation process under Article 5, member states were requested to carry out "(i) an initial assessment (IA) (. . .) of the current environmental status of the waters concerned and the environmental impact of human activities thereon (. . .); (ii) a determination (. . .) of GES for the waters concerned (. . .); (iii) establishment of a series of environmental targets (ETs) and associated indicators" by July 15, 2012 (EU-COM, 2008).

This assessment should have been done in the context of "waters, the seabed, and subsoil on the seaward side of the baseline from which the extent of territorial waters is measured extending to the outmost reach of the area where a Member State has and/or exercises jurisdictional rights, in accordance with the Unclos (. . .)" (Article 3.1a; EU-COM, 2008). Moreover, it should have taken into account regional and subregional subdivisions of the MSFD as identified under Article 4 of the directive (EU-COM, 2008). In doing so, member states were asked to coordinate with the other EU states and other countries with national waters within the same region or subregion using "existing regional institutional cooperation structures, including those under Regional Sea Conventions, covering that marine region or subregion" (Article 6.1; EU-COM, 2008).

After consulting all interested parties, the Commission issued the decision on criteria and methodological standards for the GES of marine waters for implementation of the MSFD (Commission Decision 2010/477; EU-COM, 2010). This defined the qualitative description of GES in relation to 11 descriptors, along with a set of related criteria and indicators to be applied for quantitative assessment. In particular, Descriptor 3 concerns commercially exploited species. Its GES is qualitatively described as the condition where "populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock" (Annex, Part B, EU-COM, 2010). The commission decision stated that stocks to be considered for the purpose of such an assessment should have included "all the stocks covered by Regulation (EC) No. 199/2008 (within the geographical scope of Directive 2008/56/EC) and similar obligations under the Common Fisheries Policy (CFP). For these and for other stocks, its application depends on the data available (taking the data collection provisions of Regulation (EC) No. 199/2008 into account), which will determine the most appropriate indicators to be used" (Annex, Part B, EU-COM, 2010).

Regulation (EC) No. 199/2008 (EU, 2008) refers to the Data Collection Framework (DCF) established in 2000 within the CFP for the collection and management of fishery data. Under this framework, the member states collect, manage, and provide a wide range of fisheries data for the main stocks, which are selected by DCF according to their relevance in terms of both landings and value. Such data include both the biological data (e.g., landings and catches by métier, fishery independent data) and socio-economic data (e.g., employment, revenues, etc.) needed for scientific advice. Accordingly, the definition of stocks to be considered within the MSFD established the need for including all stocks for which DCF applies, thus determining a clear link between the MSFD and the CFP.

The three criteria to be considered for the assessment of GES by member states included fishing pressure, reproductive capacity, population age and size distribution, whose assessment is based on a suite of primary and secondary indicators (**Table 1**). Moreover, the first two criteria adopt, in the case of primary indicators, MSY-related reference points. The reformed CFP was delivered in 2013, 5 years after establishing the MSFD and 3 years after the definition of MSFD criteria and methodological standards by the Commission. The new basic regulation of the CFP is aligned to the overall objectives of the MSFD in relation to Descriptor 3, as the CFP is aimed at implementing measures to gradually reach biomass levels capable of producing the maximum sustainable yield (MSY; spawning stock biomass - SSB above B_{MSY}) by 2015 where possible, and no later than 2020. Moreover, the two policies in relation to commercial fish and shellfish are interrelated and it is among the purposes of CFP to contribute to achieving GES (Article 2j; EU, 2013). In addition, the monitoring activities carried out within the DCF are some of the main providers of data to support the implementation of the MSFD, and not only in relation to commercially exploited species (Zampoukas et al., 2014).

The Report from the Commission to the Council and the European Parliament on the first phase of implementation of the MSFD (COM 2014/97 final; EU-COM, 2014) showed a limited degree of coordination among member states in relation to several descriptors. This condition was also confirmed in a study by Crise et al. (2015) on Southern European seas, which also pointed out the issue of the lack of data for the implementation of GES for some descriptors, as well as an imbalance in MSFD implementation between coastal and off-shore areas. Regarding

TABLE 1 | Criteria, primary and secondary indicators, and associated threshold levels, for the assessment of GES in relation to Descriptor 3, according to MSFD Criteria and Methodological Standards (EU-COM, 2010).

Criteria	Primary indicators	Threshold level	Secondary indicators	Threshold level
3.1. Level of pressure of the fishing activity	Fishing mortality (F) (3.1.1)	$F_{MSY} \leq$ Fcurr	Ratio between catch and biomass index (hereinafter "catch/biomass ratio") (3.1.2)	Time series analysis and expert judgment
3.2. Reproductive capacity of the stock	Spawning stock biomass (SSB) (3.2.1)	SSB > SSB_{MSY}	Biomass indices (3.2.2)	Time series analysis and expert judgment
3.3. Population age and size distribution	Proportion of fish larger than the mean size of first sexual maturation (3.3.1) Mean maximum length across all species found in research vessel surveys (3.3.2) 95 % percentile of the fish length distribution observed in research vessel surveys (3.3.3)	Time series analysis and expert judgment	Size at first sexual maturation, which may reflect the extent of undesirable genetic effects of exploitation (3.3.4)	Time series analysis and expert judgment

Descriptor 3, the report from the Commission (EU-COM, 2014; EU-COM Annex, 2014) identified the lowest degree of coherence at the regional level in relation to IA, GES, and ET definition across the Mediterranean subregions, while medium coherence was achieved in the Northern Seas (NE Atlantic), which was confirmed by the International Council for the Exploration of the Sea (ICES, 2014a).

This outcome is quite relevant since the Mediterranean Sea, a large marine ecosystem characterized by high biodiversity (Coll et al., 2010), is subjected to an intensive fishing pressure, with about 90% of assessed stocks showing clear signs of overexploitation (Colloca et al., 2013). Despite the alarming evidence of excessive fishing mortality (Fcurr >> F_{MSY}) exerted on exploited populations (Vasilakopoulos et al., 2014; Tsikliras et al., 2015), fishing pressure has not been reduced in the last decade for most species (Cardinale and Scarcella, 2017). In the whole Mediterranean and Black Sea Basin, fishery management is carried out in the framework of the General Fisheries Commission for the Mediterranean (GFCM). The GFCM is a Regional Fisheries Management Organization (RFMO) that plays a role in coordinating efforts by governments to effectively manage fisheries at the regional level following the FAO Code of Conduct for Responsible Fisheries (FAO, 1995).

However, for EU member states with national waters in the Mediterranean and Black Sea Basins, the prescriptions of the CFP also apply. At present, the main EU fishery legislations for this area include the Mediterranean Regulation [Council Regulation (EC) No. 1967/2006; EU, 2006] and the reformed CFP [Regulation (EU) No. 1380/2013, EU, 2013]. Landings from EU member states account for about 87% of the total Mediterranean landings (average for the 2011–2014 period based on FAO Fishstat data). The CFP is associated with a financial instrument [Regulation (EU) No. 508/2014; EU, 2014] that allows co-financing data collection [Council Regulation (EC) No. 199/2008, EU, 2008; Commission Implementing Decision (EU) 2016/1251, EU-COM, 2016]. Moreover, it supports member states for the implementation of CFP-related structural policies (e.g., reduction of fishing capacity, support to the development of processing and trading, etc.). Owing to such financial support and to the political role of the EU in managing the fishery sector of member states, the CFP is substantially more demanding than current GFCM prescriptions in terms of member-state obligations.

Given the presence of a common and coherent base of available data (i.e., DCF), the MSFD prescriptions for coordination among member states and within the Regional Sea Convention, and the recorded evidence of limited coherence within MSFD implementation in the Mediterranean Sea (EU-COM, 2014; EU-COM Annex, 2014; Crise et al., 2015), we wanted to assess and compare in detail how member states implemented the MSFD in relation to Descriptor 3, as well as identify the most critical sources of discrepancies. Our general hypothesis based on MSFD requirements is that member states should have adopted similar approaches in the selection of assessment areas, stocks to be considered, GES, and target definitions, and that within the same subregion, the approaches should have been consistent.

In this context, we analyzed the coherence of MSFD implementation at the national level across Mediterranean member states and with both MSFD and CFP objectives. The potential synergies between these two pieces of legislation were also considered in light of increasing the degree of their coherence to further support the efforts to reach fishery sustainability and GES in the area.

Accordingly, our analysis focuses on the following objectives:

1) Assessing the coherence of the selection of stocks and the extent to which the member states used data collected under the EU DCF (EU, 2008) for the purposes of IA and GES assessment within the MSFD.
2) Estimating the percentage of landings subjected to quantitative assessment of GES and comparing it to the past and future data availability given EU and GFCM obligations on data collection.
3) Providing an in-depth analysis of the approach adopted for MSFD reporting and implementation at the Mediterranean level, considering the definition of the spatial units adopted (i.e., assessment areas), GES and ET.

4) Assessing the current coherence in the implementation of the MSFD in relation to CFP objectives for commercial fish and shellfish stocks while considering the potential future impact of the recent process established under the relevant Regional Sea Convention (Barcelona Convention) and GFCM to address MSFD obligations.

These elements are also discussed in light of the recent Commission Decision (EU) 2017/848 (EU-COM, 2017) released on May 17, 2017, which updates the former decision on criteria and methodological standards for GES (EU-COM, 2010). In this context, we reflect on whether this new technical specification will ensure higher coherence in the MSFD implementation in the Mediterranean Sea for GES assessment in regard to Descriptor 3.

MATERIALS AND METHODS

Data Sources

MSFD Implementation within the Mediterranean Sea

Official reports and documentation regarding the implementation of MSFD in EU Mediterranean member states (Spain, France, Italy, Malta, Slovenia, Croatia, Greece, Cyprus, with the exclusion of Gibraltar) were retrieved between January and February 2017 from the Central Data Repository of the European environment Information and Observation Network (Eionet) (http://cdr.eionet.europa.eu/). In the "Central Data Repository" section within the folders of "Marine Strategy Framework Directive: Articles 8, 9, and 10 & geographic areas and regional cooperation reporting," a series of documents and files were inspected to gather the following information:

- Spatial units of application (i.e., assessment areas, as defined in relation to Descriptor 3).
- A list of stocks considered in the IA for each assessment area (mainly obtained from "national text-based paper reports").
- GES definitions according to each member state (Supplementary Table 1).
- ET definitions according to each member state (Supplementary Table 2).

Landings and Stock Assessments

Official EU landings statistics encompassing all commercial species obtained by each member state fleet were not publicly available at disaggregated spatial levels, such as MSFD assessment areas or FAO geographical sub-areas. Accordingly, data based on the FAO Fisheries and Aquaculture Department and stored in the GFCM (Mediterranean and Black Sea) capture production database were retrieved from the European Marine Observation and Data Network (EMODnet; Human Activities: Fish catches by FAO statistical area; http://www.emodnet-humanactivities.eu/search-results.php?dataname=Fish+Catches+by+FAO+Fishery+Statistical+Areas). The analysis was conducted using landing data from the FAO Fishery Statistics by species for the year 2011 (the closest year available in relation to when MSFD reporting on IA and GES/ET were carried out by MS). These data were assigned unambiguously to the MSFD assessment areas of member states based on the overlap between the country of origin and statistical area (**Table 2**). Only two exceptions were applied: in the case of Spain, which defined two different assessment areas joining 4 different geographical sub-areas (GSAs: 1, 2, 5, 6), all data refer to the same FAO statistical unit (i.e., Balearic, 37.1.1). Given the inconsistency between FAO statistical units and MSFD subregional domains for Italy, the official national DCF 2011 landing data toglierei la virgola by GSAs were used.

TABLE 2 | Assessment areas identified by each Mediterranean EU member states per single MSFD subregion and overlap with FAO Statistical Areas.

MSFD subregion	Member state	Main GSA associated to the assessment area	FAO statistical division
Western Mediterranean Sea (WMS)	France	GSAs 7-8	1.2–1.3
	Spain	GSAs 1-2	1.1
		GSAs 5-6	1.1
	Italy	GSA 9	1.3
		GSA 10	1.3
		GSA 11	1.3
Adriatic Sea (AS)	Slovenia	GSA 17	2.1
	Croatia	GSA 17	2.1
	Italy	GSA 17	2.1
		GSA 18	2.2
Ionian Sea and the Central Mediterranean Sea (ISCM)	Italy	GSA 16	2.2
		GSA 19	2.2
	Malta	GSA 15	2.2
	Greece	GSA 20	2.2
Aegean-Levantine Sea (ALS)	Cyprus	GSA 25	3.2
	Greece	GSAs 22-23	3.1

Data Analysis

Consistency across Spatial Units

The geographical boundaries of assessment areas as identified by member states were plotted based on coordinates provided by national reports to relate them to the GFCM GSAs and to highlight potential spatial overlap. This condition would imply that member states decided to consider for their assessment of the same area (or at least a portion), thus potentially leading to contrasting interests and methods. Analyses were carried out using QGIS 2.18.4.

Consistency in Stock Selection and Corresponding Proportion of Landings

We tested the hypothesis that member states would have selected the same species for the MSFD implementation for assessment areas which were close to each other and, in general terms, at subregional and regional levels owing to MSFD prescriptions, the common source of data (i.e., DCF), and the possible similarities in main target species and landings composition. For this purpose, two cluster analyses were performed (Bray–Curtis similarity/group average) on data in relation to each assessment area selected by member states. One considers the selected stocks and is based on presence/absence data, while the second is based on landings per species per assessment area (fourth-root transformation) by member states. The analysis was carried out using Primer 6.1.

We also assessed whether consistency was achieved among member states in terms of the proportion of landings represented by the stocks selected (i.e., the IA and reported GES corresponded to a similar percentage of landings). Accordingly, the percentage of landings of the stocks selected by member states for the purpose of the IA over total landings was computed for national assessment areas at the national level and the subregional level. Species under international management (i.e., under the International Commission for the Conservation of Atlantic Tunas - ICCAT management) were excluded from total landings. The same computation was done for species evaluated through stock assessments carried out in the period of 2010–2011 and approved by the Scientific, Technical, and Economic Committee for Fisheries (STECF; Cardinale and Osio, 2012). The latter analysis was carried out to highlight the percentage of landings in relation to stocks that provide analytical information to evaluate their status according to MSY-related reference points.

We compared the actual use of data made by member states within the MSFD implementation to the potential past, current, and future availability of data in relation to data collection obligations. To this end, we estimated the percentage of landings corresponding to stocks for which data collection is required under the following considerations:

- Stocks for which the DCF (EU, 2000, 2008; EU-COM, 2016) obligations apply.
- Species assigned a minimum landing size (MLS; now Minimum Conservation Size) according to Reg. 1967/2006 (EU, 2006) and thus subject to the reformed CFP in relation to the establishment of management plans and landing obligations.
- Stocks for which data collection is foreseen in the future according to the recent update of the Data Collection Reference Framework by the GFCM (2016).

In the latter case, we considered three groups of species: A1: stocks that drive the fishery and for which assessment will need to be carried out regularly; A2: stocks which are important in terms of landing or economic value at the regional and subregional levels, and for which assessment will not be regularly carried out; A3: species within international/national management plans and recovery or conservation action plans; non-indigenous species with the greatest potential impact (GFCM, 2016).

GES and Environmental Target Definitions

GES and ET definitions provided by each member state were analyzed in order to assess whether they were aligned to the MSFD prescriptions and objectives. For this purpose (based on official member state documentation), we assessed the following items:

1) Comprehensiveness of the application of criteria for IA and GES assessment (i.e., whether or not member states applied all criteria).
2) Exhaustiveness of the definition of commercial species to be considered for GES assessment (i.e., whether or not member states clearly defined the list of stocks to be considered for GES assessment).
3) Agreement between the national GES definition, in relation to the use of reference points for indicators 3.1.1 and 3.2.1 and MSFD technical guidelines/CFP objectives (i.e., whether member states defined MSY-related reference levels for GES assessment as targets or limits).
4) Agreement between ET and MSFD/CFP objectives (i.e., whether ETs were clearly defined ensuring to reach MSFD/CFP objectives).

RESULTS

Consistency across Spatial Units

The MSFD divides the Mediterranean region into four different subregions: the Western Mediterranean Sea (WMS); the Adriatic Sea (AS); the Ionian Sea and the Central Mediterranean Sea (ISCM); and the Aegean-Levantine Sea (ALS). Member states had to consider such geographical sub-divisions when defining the extent of assessment areas. Most assessment areas were included in each geographical subregion except for the Strait of Sicily, for which the extension partially overlapped between the WMS and ISCM subregions (**Figure 1**).

Mediterranean member states defined 16 assessment areas in total, for which the spatial extension approximately overlapped with GFCM GSAs (**Figure 1**; **Table 2**). However, while the match between assessment areas and GSAs was almost full for Italy, Malta, Croatia, and Cyprus (i.e., each GSA had a corresponding assessment area), Spain, France, and Greece defined some assessment areas that merge two GSAs. In detail, Spain considered two assessment areas, the "Strait and Alboran" and the "Levantine Balearic area," which almost overlapped with GSAs 1–2 and 5–6, respectively. France defined a single assessment area by merging waters of the Gulf of Lion (GSA 7) and the area around Corsica (GSA 8). It is worth mentioning that a clear overlap emerges between Spain's and France's assessment areas (**Figure 1**). In the Adriatic Sea, Italy, and Croatia restricted their assessment from national waters toward the midline. Within the ALS, Greece considered a single assessment area by merging waters of GSAs 22–23. The Malta assessment area was restricted to national waters and thus a sub-portion of GSA 15. In the case of Cyprus, assessment areas extended beyond the limits of GSA 25, overlapping with two other GSAs.

Consistency in Stock Selection and Corresponding Proportion of Landings within MSFD Initial Assessment

Stocks Selection

A total of 419 fish and shellfish stocks corresponding to 89 species were considered by EU Mediterranean member states for the purposes of the IA. However, limited consistency emerged in terms of the typology and number of selected stocks among assessment areas within subregions and among subregions. In particular, the number of considered stocks was uneven. Malta, Spain, Slovenia, and Italy considered between 28 to 43 stocks per assessment area, while Greece, France, Croatia, and Cyprus

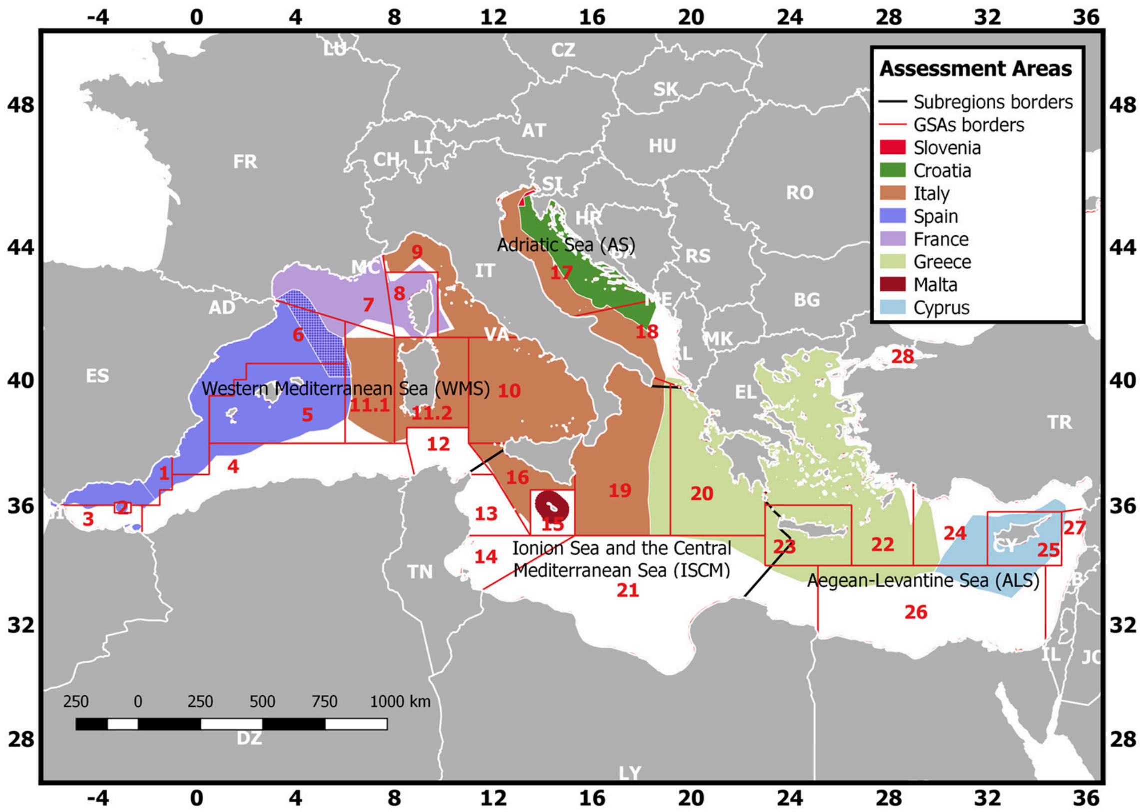

FIGURE 1 | The spatial boundaries of assessment areas identified by member states for the assessment of Descriptor 3 within the MSFD. Boundaries of FAO geographical sub-areas are also represented in the background. The area identified by the white crosses represents the overlap between France and Spanish assessment areas.

restricted their assessment to a pool of 7–11 selected stocks (**Table 3**).

This pattern is also revealed by the cluster analysis based on selected stocks by assessment areas, which shows the presence of two main clusters at a similarity level cutoff of 25% (**Figure 2**) with one outlier (Cyprus). The two clusters relate to assessment areas of high vs. low numbers of considered stocks (**Table 3**). Assessment areas displaced in 4 and 3 subregions were grouped within the two clusters, showing a lack of similarities in stock selection within subregions. High similarities were observed among stocks selected at the national level within different assessment areas and subregions, as in the case of Italy (single cluster at a similarity of about 75%), Greece, and Spain (similarity above 80% each).

Further information can be derived by comparing the outcomes of this multivariate analysis to the cluster based on landings per species per assessment area (**Figure 3**). Indeed, at the same similarity cutoff of 25%, only one major cluster is identified grouping all assessment areas apart from that defined by Slovenia. Within the main cluster, two main clusters emerge: one comprising islands (Malta and Cyprus) and another comprising all the other member states. Within the latter, Greece's assessment areas differ, while a major cluster groups Spain's and France's landings and another groups Italy's and Croatia's landings by assessment areas. This result shows similarity among landings of geographically closer assessment areas, which is higher than that observed in terms of selected stocks. Moreover, it shows consistency between landing composition across assessment areas belonging to the same member states. However, in relation to Italian landings, we point out that the high similarity shown among its GSAs could be partially due to the different data sources used for this country compared to the others (i.e., DCF data vs. FAO statistics). The combined analysis of the clusters thus shows that stock selection per assessment area for the IA was not fully consistent with respect to the variation in corresponding landing composition.

Further differences are revealed when considering the detailed list of stocks and species selected for the IA at the subregional level. In general terms, the AS subregion was the area where the largest number of species was considered (68), followed by WMS (56) and ISCM (53). Importantly, these values were higher than those of the ALS, where only a total number of 17 species was considered (**Table 3**).

Mullus barbatus was the only species for which stocks were considered in all the Mediterranean assessment areas. At the subregional scale, *Merluccius merluccius* represented a common stock in all assessment areas within all subregions apart from the ALS, while *Mullus surmuletus* was commonly considered in all assessment areas in both ISCM and ALS. *Parapenaeus longirostris* was considered in all assessment areas of ISCM, while

TABLE 3 | Number of stocks, species, and the corresponding percentage of landings considered within Initial Assessment in all Mediterranean assessment areas.

Subregion	Member state	Assessment area code	Number of stocks	% of landings	Number of species	Common species (within subregion)
Western Mediterranean Sea (WMS)	Spain	SP_1-2	29	53	56	*Merluccius merluccius, Mullus barbatus, Octopus vulgaris*
	Spain	SP_5-6	27			
	France	FR_7-8	8	41		
	Italy	IT_09	32	59		
	Italy	IT_10	39	28		
	Italy	IT_11	39	54		
Adriatic Sea (AS)	Slovenia	SLO_17	33	90	68	*Merluccius merluccius, Mullus barbatus*
	Croatia	HR_17	10	95		
	Italy	IT_17	42	50		
	Italy	IT_18	38	40		
Ionian Sea and the Central Mediterranean Sea (ISCM)	Italy	IT_16	43	84	53	*Merluccius merluccius, Mullus barbatus, Mullus surmuletus, Parapenaeus longirostris*
	Italy	IT_19	28	30		
	Malta	ML_15	26	23		
	Greece	GR_20	7	42		
Aegean-Levantine Sea (ALS)	Greece	GR_22-23	9	38	17	*Mullus barbatus, Mullus surmuletus, Spicara maena*
	Cyprus	CYP_25	11	35		

Species commonly selected at subregional level (in all assessment areas) are also reported.

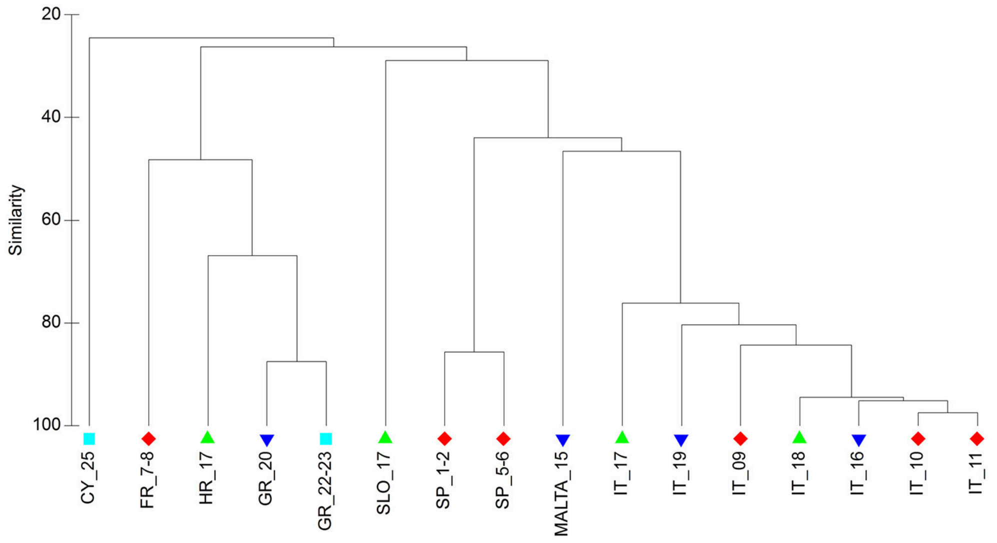

FIGURE 2 | Cluster analysis (group average, based on Bray–Curtis similarity matrix) of stocks selected per assessment areas (presence/absence data) within the MSFD Initial Assessment in the Mediterranean Region. ◆ : Western Mediterranean Sea; ▲ : Adriatic Sea; ■ : Ionian Sea and Central Mediterranean; ▼ : Aegean-Levantine Sea. Assessment areas codes are reported in **Table 3**.

Octopus vulgaris and *Spicara smaris* were commonly assessed within WMS and ALS, respectively.

Proportion of Landings

The proportion of landings corresponding to the stock selected by member states within the IA largely varied among assessment areas (**Table 3**). Overall, member states selected stocks representing different shares of national landings, with the highest values recorded for Slovenia and Croatia (above 90%), intermediate levels for Spain, France, and Italy (between 40 and 60%), and low levels for Malta, Greece, and Cyprus (between 20 and 40%; **Figure 4**). The comparison between landing percentages considered within IA and those related to data collection and policy obligations already established before shows that member states possibly did not use all potentially available scientific data. Indeed, landings associated with stocks

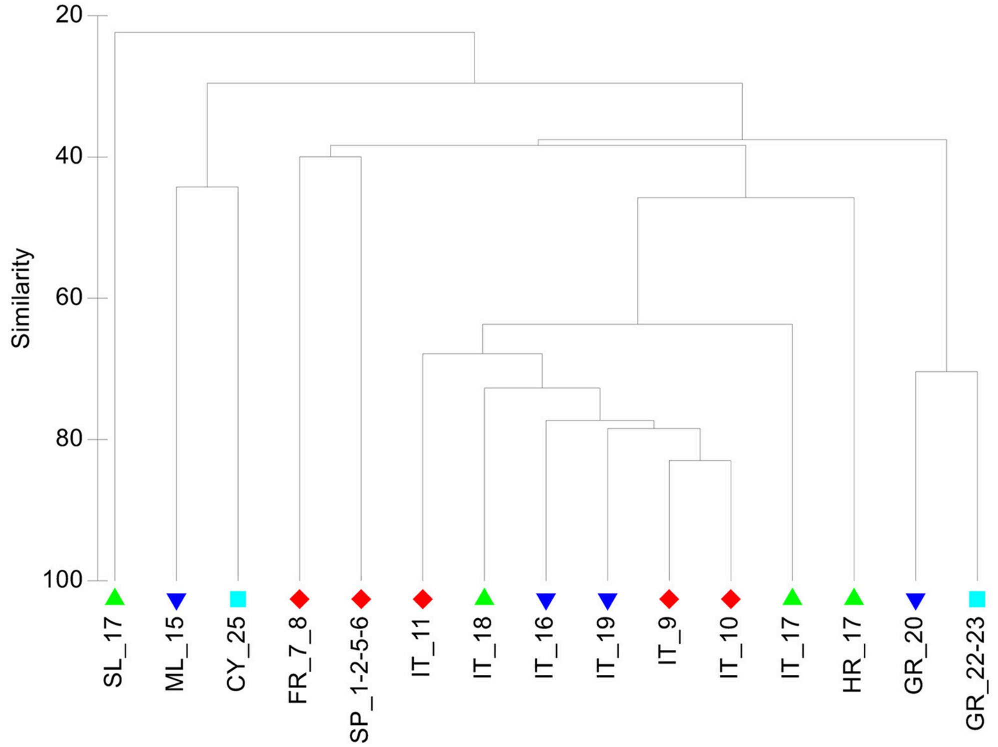

FIGURE 3 | Cluster analysis (group average, based on Bray–Curtis similarity matrix) of landings composition per species and assessment areas (fourth root transformation) within the MSFD Initial Assessment in the Mediterranean Region. ◆ : Western Mediterranean Sea; ▲ : Adriatic Sea; ■ : Ionian Sea and Central Mediterranean; ▼ : Aegean-Levantine Sea. Assessment areas codes are reported in **Table 3**.

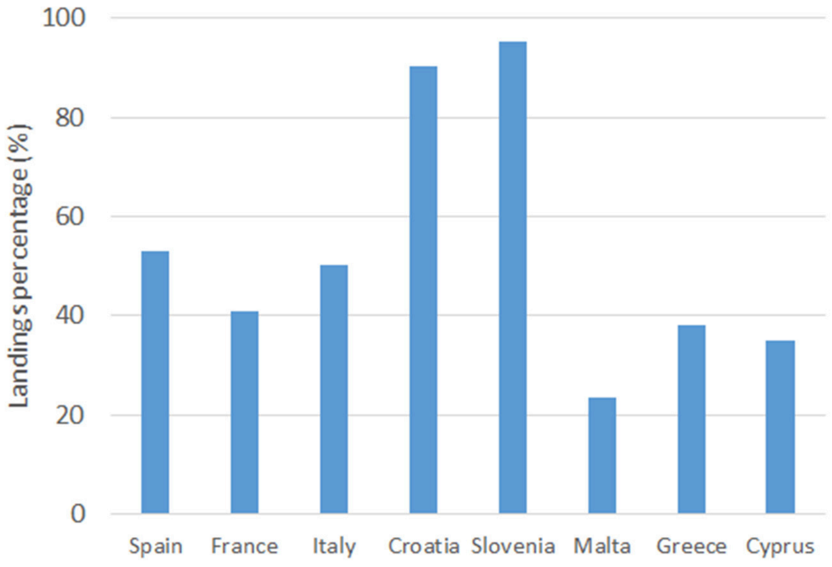

FIGURE 4 | Percentage of landings corresponding to the stocks selected by the EU member states within their Initial Assessment.

monitored under the DCF (EU, 2008) were higher than those considered for the IA (**Figure 5**). Even the landings associated with species for which MLS was established according to EU (2006) were higher than those assessed within the IA at the subregional level, apart from the case of WMS. It is also worth noting that when IA was carried out, only a minor share of

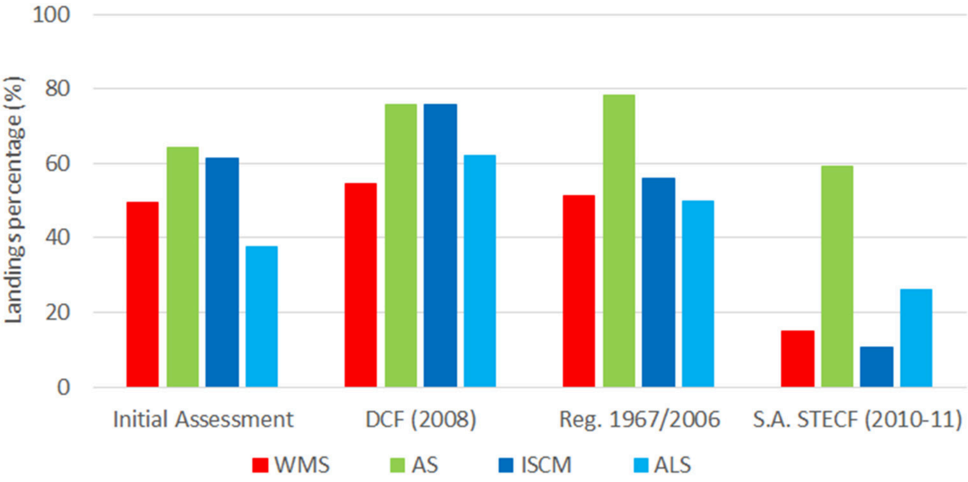

FIGURE 5 | Percentage of landings corresponding to the stocks considered by EU member states within their Initial Assessment and in relation to data collection and policy obligations. Estimates are given at MSFD subregional level. WMS, Western Mediterranean Sea; AS, Adriatic Sea; ISCM, Ionian Sea and Central Mediterranean; ALS, Aegean-Levantine Sea. DCF (2008): Percentage of landings corresponding to stocks' list object of the DCF (EU, 2008). Reg. 1967/2006: Percentage of landings corresponding to species subjected to Minimum Landings Size according to the Mediterranean Regulation (Appendix 3, EU, 2006). S.A. STECF: Percentage of landings corresponding to stocks which were assessed on 2010–2011 by STECF (Cardinale and Osio, 2012).

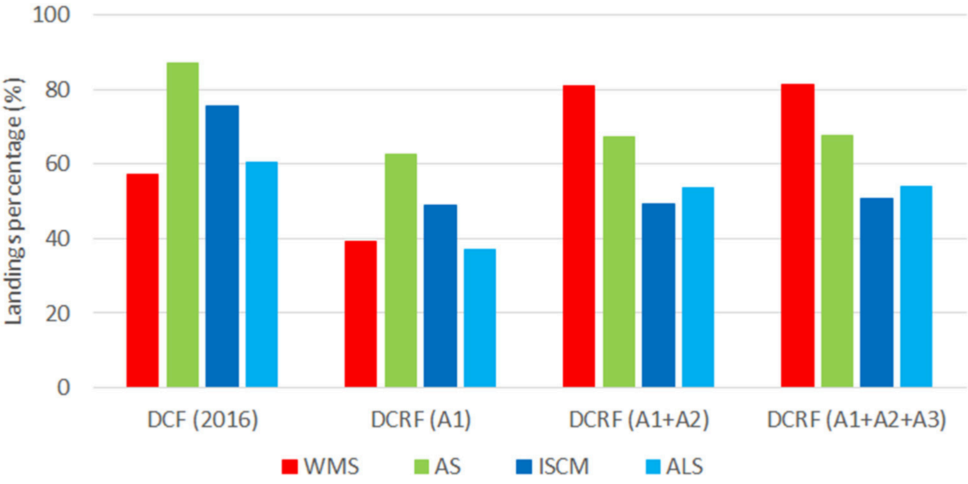

FIGURE 6 | Percentage of landings whose data collection is required under recently reviewed international obligations. Estimates are given at MSFD subregional level. WMS, Western Mediterranean Sea; AS, Adriatic Sea; ISCM, Ionian Sea and Central Mediterranean; ALS, Aegean-Levantine Sea. DCF (2016): percentage of landings corresponding to stocks' list object of the recent revision of DCF (EU-COM, 2016). DCRF: Percentage of landings corresponding to stocks' list object of the recent revision of the GFCM Data Collection Regional Framework (FAO, 2016). A1: Stocks that drive the fishery and for which assessment is regularly carried out; A2: Stocks which are important in terms of landing and/or economic values at regional and subregional level, and for which assessment is not regularly carried out; A3: Species within international/national management plans and recovery and/or conservation action plans; non-indigenous species with the greatest potential impact.

landings was associated with consolidated stock assessments (i.e., those approved by STECF in 2010–2011; Cardinale and Osio, 2012), thus implying that the application of primary indicators associated with MSFD criteria 3.1 and 3.2 was restricted to a small number of stocks.

Future Scenarios of Data Availability

The DCF has recently been revised (EU-COM, 2016), and according to the new set of stocks that will need detailed data collection, a slight increase in the coverage of landings per subregion will be achieved (**Figure 6**). Recently, the Data Collection Regional Framework by GFCM (FAO, 2016) has been further amended with a request to collect data on a larger share of stocks across the Mediterranean. This is expected to increase the percentage of landings of stocks associated with the formal stock assessment from about 40–60%, depending on the subregion (**Figure 6**). However, the assessment will be regularly carried out for only a relatively small set of stocks (A1 species), including five species in all Mediterranean subregions (i.e., *Engraulis encrasicolus*, *Sardina pilchardus*, *M. barbatus*, *M. merluccius*, *P. longirostris*) and two species assessed in 3 out of 4 subregions (i.e., *M. surmuletus* and *Nephrops norvegicus*). Moreover, for other species (A2 species), assessment will not be regular. Based on the availability of both A1 and A2 data, between 50% (ISCM) and 81% (WMS) of landings could be associated with data to assess GES. Considering vulnerable species within international/national management plans, recovery, and conservation action plans (A3 species) will not substantially improve this figure.

Methodological Implementation

GES and Environmental Targets Setting

Most member states applied the IA and defined GES at the Descriptor 3 level or in relation to criteria 3.1 and 3.2. Conversely, for Criteria 3.3, only France, Italy, Slovenia and Cyprus provided some description of GES interpretation, which were quite vague in some cases (Supplementary Table 1). Three major discrepancies in comparison to MSFD criteria definitions and objectives emerge (**Table 4**):

1) A lack of specification of stocks to be considered (e.g., Greece).
2) Reference points for single stocks (e.g., F_{MSY}) which were considered as targets and not limits (e.g., Spain and France).
3) A lack or preliminary definition of threshold levels; i.e., the percentage of stocks that need to be within safe biological limits to consider GES to be achieved (e.g., Italy).

In total, member states defined 31 ETs referred to Descriptor 3 (Supplementary Table 2). Among the selection of those mainly related to commercial fishing practices, most of the ETs referred to GES achievement, while a smaller part represented interim targets (**Table 5**). However, the agreement with MSFD objectives was overall limited. These inconsistencies included:

1) A lack of detailed definition of stocks for which the target should be achieved (e.g., Spain, France, Slovenia, Greece).
2) The setting of objectives that are less ambitious than MSFD objectives and promote stability rather than improvement (where necessary) of stock status (e.g., Croatia).
3) The lack of clear definition of targets in relation to policies (such as the CFP) that still needed to be issued when ETs were proposed (e.g., Italy, Cyprus).

Depending on the member state, targets not explicitly related to the GES definition and achievement were considered (Supplementary Table 2). These included the regulation of recreational fishing (i.e., Slovenia, Italy); the improved monitoring of biological resources (e.g., Greece, Cyprus); the establishment of MLS for selachians and the control of illegal, unreported, and unregulated fishing (IUUF) (i.e., Italy); and the sustainability of artisanal fishing (i.e., France).

DISCUSSION

The MSFD represents an unprecedented effort to implement an ecosystem approach in marine waters in a large area like European marine waters, encompassing several countries and ecosystems, and establishing a holistic functional approach (Borja et al., 2010). This process was based on the definition of GES in relation to 11 descriptors, which consider the majority of marine ecosystem components and pressures. The Commission provided technical guidelines to support member states in MSFD implementation and fostered the coordination among member states and other countries thanks to the role of Regional Sea Conventions. Among the 11 MSFD descriptors, Descriptor 3 is not the only one connected to fisheries and their impact on the marine environment, with partial overlap with biodiversity, the marine food-web and seafloor integrity (Descriptors 1, 4, and 6, respectively). In this paper, we focused on Descriptor 3 related to commercial fish and shellfish and considered the approach

TABLE 4 | Main elements of discrepancies arising from the comparison between member states GES definition according to Descriptor 3 criteria in respect to MSFD criteria definition (EU-COM, 2010).

Member state	Criteria 3.1: Fishing pressure	Criteria 3.2: Reproductive capacity	Criteria 3.3: Population age and size distribution
SPAIN	F_{MSY} considered as a target	SSB considered as a target	NA
FRANCE	F_{MSY} considered as a target	SSB considered as a target	Vague definition
ITALY	F_{MSY} considered as a limit. Preliminary thresholds	SSB limits poorly defined. Preliminary thresholds	Trend based definition
CROATIA	F_{MSY} not clearly defined as a limit. Application only to assessed stocks—no use of secondary indicators	SSB not clearly defined as a limit. Application only to assessed stocks—no use of secondary indicators	NA
SLO	F_{MSY} considered as a limit. Use of secondary indicators	SSB_{MSY} considered as a limit	Reference points not defined for 3.3.1. Trend based analysis for 3.3.3
MALTA		GES not defined adequately	
GREECE	GES not defined adequately. F_{MSY} limits applied only to undefined selected stocks	GES not defined adequately. SSB limits applied only to undefined selected stocks	NA
CYPRUS	Unclear if all stock should be below F_{MSY}	Unclear if all stock should be above SSB_{MSY}	No operational definition

NA, criteria not considered. The full definition of GES by member states per descriptor/criteria/indicators is reported in Supplementary Table 1.

TABLE 5 | Selected list of environmental targets defined by Mediterranean EU member states in the early phases of MSFD implementation.

Member state	Environmental targets	Type of target/ indicator	Interim or GES target?
SPAIN	Ensure that fish stocks are properly managed so that they remain within safe biological limits.	Operational	GES
FRANCE	Develop professional fishing practices compatible with the maintenance of living resources in the Gulf of Lion and coastal areas, at sustainable harvesting levels.	Pressure	GES
ITALY	For those stocks that show signs of overfishing ($F > F_{MSY}$ or $E > E_{MSY}$), or that are overexploited (SSB < SSBref level), or show signals pointing to an ongoing significant alteration of their age structure/reproductive capacity according to indicators 3.2.2, 3.3.1, and 3.3.3, a reduction in fishing mortality aligned with the objectives that will be defined in the forthcoming reform of Common Fisheries Policy (CFP) will be implemented.	Pressure	Interim
CROATIA	(a) Demersal fish: long-term stability of distribution, biomass and abundance of targeted species in the assessment area. (b) Demersal fish: long-term stability of demersal communities in the assessment area. (c) Pelagic fish-anchovy: long-term stability of anchovy eggs and larvae abundance. (d) Pelagic fish-sardine: long-term stability of sardine eggs and larvae abundance. (e) Shellfish: long-term stability of targeted species biomass indices.	State	GES
CROATIA	(a) Demersal fish: the demographic structure remains unchanged. (b) Pelagic fish-anchovy: the demographic structure, sex ratio and batch fecundity remain more or less stable over time. (c) Pelagic fish-sardine: the demographic structure, sex ratio and batch fecundity remain more or less stable over time. (d) Coastal fish: long-term stability of the composition, biomass indices and length structure of targeted species. (e) Shellfish: the demographic structure of targeted species remains more or less stable over time.	State	GES
SLOVENIA	By 2018, the need to reduce fishing mortality to a level which will ensure sustainable use. Related objectives: the stock of sole (*Solea solea*) is overfished, thus a reduction of F is recommended, particularly the use of dredges. Two-month ban on fishing with dredges at the distance from 11 km from the Italian coast; closures for the reduction in the catch of juveniles. Stock of sardine (*Sardina pilchardus*) is fully exploited, thus fishing effort should not increase. It must also interact with the fishery for anchovy. Anchovy (*Engraulis encrasicolus*) is fully exploited, thus fishing effort should not increase.	Operational	Interim
SLOVENIA	By 2018, fishing effort should be reduced by x% for all species, basing on studies that found a reduced ability to reproduce or a modified age/size structure of populations.	Pressure	Interim
MALTA	Management and monitoring of fishing activities result in a sustainable fishing effort over time, in line with the measures put forward in Malta's Fisheries Management Plans, with a view to ensuring sustainability of the stocks targeted by Maltese fisheries.	NA	NA
GREECE	Correlation of the fishing activities with the designated indicators. Associated indicators: The F/F_{MSY} and B/B_{MSY} ratios for main target demersal species and the exploitation rate of main target pelagic species should be within the designated thresholds as defined by National and EU Legislation.	Operational	Interim
CYPRUS	Populations of all commercially exploited fish and shellfish should approach safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock. All ICES, ICCAT, and GFCM recommendations in that direction will be followed, within the framework of the European Common Fisheries Policy.	State	GES

The full list of environmental targets established by member states is reported in Supplementary Table 2. Only targets mainly focused on commercial fisheries are reported.

and outcomes of the early phases of MSFD implementation. The focus was the Mediterranean Sea, an area that shows critical signs of overexploitation (Cardinale and Scarcella, 2017). Our analysis shows a potentially critical lack of coherence among member states in the implementation of the MSFD. Such inconsistencies can be observed at several levels, particularly: (i) the stocks selected for the implementation of the IA and the corresponding share of landings; (ii) GES definitions; and (iii) ET definitions.

Stock Selection

Stock selection was uneven within the whole basin, with only a single species considered in all assessment areas, i.e., *M. barbatus*. A similar result emerged at subregional scale, with only 3–4 stocks in common among subregions. While limited consistency was observed at these levels, member states applied consistent approaches within the assessment areas they defined.

Owing to these discrepancies, it is clear that any IA would have resulted in inconsistent and incomparable outcomes (even in the case of identical analytical approaches applied to define GES and integrate data among assessment areas). Some member states selected a relatively large number of stocks for each assessment area, while others restricted their analysis to a more restricted pool. In the case of Croatia, the latter choice did not impede representing a large portion of landings, which was above 90%. This outcome is the effect of the high incidence of small pelagics in the total national landings, particularly *S. pilchardus* and *E. encrasicolus*.

Landings characterized by a high number of commercial species are typical of the Mediterranean Sea owing to the presence of multispecific fisheries and varied seafood cultural habits (Farrugio et al., 1993). This contrasts with the North-East Atlantic region, where there are a limited number of stocks for the bulk of landings. Moreover, in the Mediterranean Sea, about 80% of the fishing vessels are from small-scale fisheries, which have clear practical difficulties with monitoring their catches of local stocks (FAO, 2016).

When comparing the potential availability of data for exploited stocks arising from the EU DCF (EU, 2008) in the Mediterranean Sea with the number of stocks selected for the IA, it appears that only a small fraction of stocks monitored under DCF were considered. This mismatch could be partially due to the quality or availability of data, which can be affected by species with low catchability or high variability within standardized surveys, spawning periods not coinciding with data collection periods, relatively short time-series, etc. Such factors might have affected the possibility of estimating some indicators in relation to different MSFD criteria. It must also be considered that criteria adopted to select stocks within assessment areas influenced this outcome. For instance, Spain selected only species for which landings were above 1% of the total landings within the considered assessment areas. Other member states did not consider some species with large landings, as in the case of *Chamelea gallina* in GSA 17. All of this is linked to an uneven interpretation of the criteria for Methodological Standards (EU-COM, 2010), which requested that "all commercial species" be considered, explicitly referring to the scientific data collected under the DCF (EU, 2008).

However, we highlight that our estimates should be taken with some caution since they were based on FAO statistical data (apart from Italy) and are referred to 2011. These data could differ to some extent from national statistics or DCF data, which are usually not fully accessible at the GSA level. For instance, Spain reported covering about 70–90% of national landings per assessment area referring to average values 2008–2010. Such estimate includes species assessed by ICCAT (which were excluded in our analysis). These values are quite different from our estimations referred to 2011 landings (53% in total), even though we considered the same set of species. Moreover, Spain reported that out of the 29 and 27 stocks they selected in relation to GSAs 1–2 and 5–6, only in 22 and 23 stocks indicators were applicable, due to lack of data.

It is worth mentioning that after the initial steps of the MSFD were implemented (early 2013), member states defined monitoring programs to fill the gaps of knowledge that emerged, defined the programmes of measures, and in some cases had already refined the species list to be considered in their assessments. However, different approaches can be identified. For instance, in 2015, Malta increased the number of species to be considered, including taxa not previously considered (e.g., cephalopods). In contrast, in the process of carrying out the monitoring programs, Italy amended some previous definition of GES. In this context, Italy identified commercial species to be considered as "those under Reg. 1967/2006, provided that they belong to G1 and G2 MEDITS species or they are MEDIAS species" (free translation from Decree of the Ministry of Environment of 17 October 2014; Decree 2014; MEDITS: International bottom trawl survey in the Mediterranean; MEDIAS: Mediterranean Acoustic Survey on Small Pelagics). These new selection criteria would sharply reduce the number of stocks considered per assessment area in the forthcoming assessment to 11 stocks, in contrast to the average of 36 stocks that were included in the previous assessment (**Table 3**).

GES and Environmental Target Setting

Further inconsistencies emerge when considering the definition of GES and ETs by member states. Overall, the definition of GES differed among member states and within subregions in relation to: (i) different interpretations or limited description of which stocks should be considered for GES assessment; (ii) whether to consider MSY-related reference points as targets or limits; and (iii) which shares of stocks should be within safe biological limits to achieve GES. Each of these items would produce different outcomes in terms of GES assessment and requirements to achieve GES. Indeed, applying different criteria for selecting stocks prevents member states from conducting assessments on similar stocks or similar shares of landings. At the same time, using MSY-related reference points as a target allows for the possibility of being above or below the reference point, which is less restrictive than setting the reference point as a limit. In addition, using different criteria to achieve GES in terms of the percentage or number of stocks that must be within safe biological limits would also have implications in the measures to be adopted to achieve GES. In this context, following a strict application of the MSFD criteria and methodological standards would have implied the inclusion of all stocks for which data are collected under the DCF in the assessment, the use of MSY-related reference points as limits, and the need to have 100% of stocks in safe biological limits to reach GES.

These discrepancies across member states clearly prevented a coherent definition of GES criteria. Moreover, only some countries adopted and defined GES in relation to secondary indicators, particularly for indicators of Criteria 3.3 (population age and size distribution). The latter case could possibly be linked to the lack of agreement on procedures to define reference limits to assess indicators of Criteria 3.3. Indeed, the recent advice proposed by ICES in relation to length-based indicators suggests that related indicators are not fully operational and that additional research will be needed to reach a consensus on defined reference levels (ICES, 2017).

Some member states applied GES estimation considering only assessed stocks, or in some cases applying secondary indicators associated with F_{MSY} and SSB_{MSY} as primary indicators. However, restricting the analysis to only stocks formally assessed under a quantitative stock assessment procedure would clearly restrict the share of landings subjected to GES assessment, especially in the case of the Mediterranean Sea. Indeed, although the number and range of stock assessments have increased in the last decade, the share of landings for which such assessments were available at the time of MSFD implementation ranged between 10 and 30% in three subregions (ISCM, WM, ALS), and up to 60% in the case of the AS.

The application of the Data Collection Regional Framework (DCRF) from GFCM might substantially improve such figure, reaching coverage between 40 and 60% for all subregions in relation to stocks for which assessment will be routinely carried out (GFCM, 2016; A1 list species). If such an approach will be extended to stocks not regularly assessed, such figures will increase to a range of 50–80% depending on the subregion (GFCM, 2016 A2 list species). Levels that are similar (yet different in relation to subregions) should be achieved in the future according to the application of the revised DCF (EU-COM, 2016).

The ETs set by member states might not be considered fully compliant with the MSFD expectations, as in the case of GES definitions. Again, the major reasons for such discrepancies are a lack of clarity on some definitions, a set of targets that are less ambitious than the MSFD objectives, or the reference to policies that were not already established when the targets were defined. Some member states justified the choice of not defining the percentage of stocks for which GES should be achieved by mentioning the intrinsic difficulties derived from ecosystem interactions and environmental fluctuations of having all commercial stocks simultaneously at MSY levels. Indeed, as pointed out by Link (2002), the sum of single species MSY is greater than MSY for the ecosystem, and it is energetically impossible to simultaneously maximize yield for multiple species. This issue was also acknowledged by Borja et al. (2013), who suggested revising the 100% threshold (i.e., all stocks should be in safe biological limits) and applying a lower operational threshold. The definition of such threshold would in turn affect the process of stocks selection moving from single stocks consideration to a proper ecosystem based approach implementation.

Moving Forward toward the 2018 Assessment and GES Goals for 2020

From our analysis, major inconsistencies among member states in the implementation of the IA and the definition of GES and ETs emerged at Mediterranean level. In contrast, at the national level, coherent approaches were applied in the case of several assessment areas, whether or not being displaced in one or more subregions. This in turn shows that the approaches were not appropriately coordinated at a subregional level as well.

In particular, the use of reference points based on MSY values as targets rather than limits is inconsistent with not only the MSFD criteria and methodological standards (EU-COM, 2010) but also with CFP objectives. However, it is worth mentioning that the latter were defined in 2013 after the MSFD was issued (EU, 2013). This lack of coherence reflected in ETs that are less ambitious than the MSFD policy objectives is likely to have hampered the potential synergies between MSFD and CFP.

As mentioned, member states sharing a marine region or subregion should have cooperated to ensure that the measures required to achieve the objectives of MSFD would have been coherent and coordinated across marine regions or subregions. In particular, existing regional institutional cooperation structures, including those under Regional Sea Conventions, were identified by MSFD as the tool for coordination between member states and other countries whose national waters are comprised within the same region or subregion and then for the enforcement of a regional approach to fishery management between EU member states and non-EU countries.

For this purpose, at the Mediterranean level and in the context of the Barcelona Convention, the UNEP/MAP established the Ecosystem Approach (EcAp) process, as agreed by the Conference of the Parties in 2008 (Decision IG17/6; UNEP, 2008) aiming to achieve GES in the Mediterranean by 2020. This process entails engaging all contracting parties (both EU and non-EU Mediterranean countries) in the definition of GES, related indicators, ecological objectives, and monitoring process. However, as pointed out by Cinnirella et al. (2014), differences between MSFD and EcAp are also evident because the latter has no financial support and applies to all Mediterranean countries. There is thus a high imbalance in terms of the economic development of countries involved compared to EU Mediterranean countries.

The lack of coherence in the MSFD implementation among Mediterranean EU member states (a problem that has emerged also in the context of other EU regions; van Leeuwen et al., 2014) also possibly derives from the difficulties in achieving a consensus among Mediterranean countries on indicators and methodologies to be applied for GES assessment within EcAp. Moreover, as shown by Freire-Gibb et al. (2014), there is uncertainty in the respective roles of different authorities responsible for executing the MSFD (i.e., the European Union, member states and Regional Sea Conventions), particularly in relation to their levels of authority, which might have been a key issue in preventing coordination among member states.

In the context of the Barcelona Convention, there has been a long revision process (that was also triggered by involving GFCM for technical support) of fishery-related ecological objective (i.e., Populations of commercially exploited fish and shellfish are within biologically safe limits; EO3). The definition of indicators as well as technical and data requirements has recently been subjected to strong improvements. Indeed, the 19th Meeting of Contracting Parties (Decision IG.22/7; UNEP, 2016) held in February 2016, adopted the EcAp-based Integrated Monitoring and Assessment Programme (IMAP) of the Mediterranean Sea and Coast and Related Assessment Criteria, for which EO3 (corresponding to MSFD Descriptor 3) is still to be consolidated. However, candidate indicators have been defined and include: SSB, total landings, F, fishing effort, catch per unit of effort or landing per unit of effort as a proxy, and bycatch of vulnerable and non-target species (UNEP, 2016). The involvement of GFCM in the definition of target species, fishing-related GES, common indicators, and ecological objectives has strengthened the coherence between EcAp-IMAP and MSFD objectives for Descriptor 3, even if there are still some differences in the defined process. In particular, no secondary indicators have been defined in relation to fishing pressure and SSB. However, the EO3 definition is now benefiting from the enforcement of the GFCM Data Collection Regional Framework (GFCM, 2016), which should boost data availability in the future in parallel to the new DCF (EU-COM, 2016).

The definition of stocks and data availability is only a part of the process to achieve regional and subregional coherence in GES assessment for Descriptor 3. Indeed, in our analyses, we did not consider methodological approaches adopted to assess indicators based on time-series and to aggregate information from multiple indicators and criteria from assessment areas to the national and subregional level. For the first item, many approaches could be applied (e.g., Spearman rank correlation, linear regressions, etc.; ICES, 2014b), and a regional coherence in the approach would be needed to ensure consistency. Coherence is also needed in regard to aggregation methods. As shown by Borja et al. (2014), the vast range of methods could result in inconsistent outcomes.

The New Scenario Arising from the Recent Revision of Criteria and Methodological Standards for GES

On May 17, 2017, the Commission Decision (EU) 2017/848 (EU-COM, 2017) was issued as an update of the former decision on criteria and methodological standards on GES of marine waters. This decision is aimed at improving the consistency of methodological approaches in relation to GES assessment. In relation to Descriptor 3 and when considering the Mediterranean subregion (Annex, Part I, EU-COM, 2017), several elements emerge in relation to the main issues we identified, i.e., the spatial scale, selection of stocks, interpretation of reference points, use of trend-based indicators, and criteria for the aggregation of information from several stocks.

In regard to the spatial scale, the Commission Decision states that "populations of each species are assessed at ecologically relevant scales within each region or sub-region, as established by appropriate scientific bodies referred to in Article 26 of Regulation (EU) No. 1380/2013 based on specified aggregations of GFCM geo-graphical sub-areas" (EU-COM, 2017). This statement clarifies that GSA aggregations could be considered and also assigns a role to the STECF in the definition of the appropriate spatial scale to be considered.

In relation to the selection of stocks to be included in GES assessment, "Member States shall establish through regional or subregional cooperation a list of commercially exploited fish and shellfish," (...) taking into account Council Regulation (EC) No. 199/2008, "all stocks that are managed under Regulation (EU) No. 1380/2013; the species for which minimum conservation reference sizes are set under Regulation (EC) No. 1967/2006; the species under multiannual plans according to Article 9 of Regulation (EU) No. 1380/2013; the species under national management plans according to Article 19 of Regulation (EC) No. 1967/2006; any important species on a regional or national scale for small-scale/local coastal fisheries," among others (EU-COM, 2017). This requirement should foster an increase in the consistency of stock selection for GES assessment within the Mediterranean Region and subregions. In this context, the role of the Barcelona Convention and GFCM will be essential to ensure that consistency will be achieved. However, the lack of clear specifications of a minimum requirement (e.g., % of landings, the number of common stocks) does not allow for current inference of how many stocks will be considered.

All three criteria (F, SSB, and age-size distribution) shall be considered, although it is recognized that data for age-size distribution might be not available for the 2018 assessment. Given the lack of consolidated reference points for related indicators, this condition will most likely result in an unbalanced application of this criterion among member states. Reference levels of F and SSB are mentioned as limits. Moreover, "In relation to stocks managed under a multiannual plan according to Article 9 of Regulation (EU) No. 1380/2013, in situations of mixed fisheries, the target F and the biomass levels capable of producing MSY shall be in accordance with the relevant multiannual plan" (EU-COM, 2017). This definition will increase consistency in the GES assessment for stocks for which analytical assessment is available, since the use of reference points as targets should not be an option. Moreover, it will increase the alignment with management plans established under the CFP. However, regarding stocks for which secondary indicators (i.e., catch/biomass ratio, and biomass related indexes) will be considered, "An appropriate method for trend analysis shall be adopted (e.g., the current value can be compared to the long-term historical average)." We highlight that without an agreed common analytical approach at the regional level for the application of trend analyses, high inconsistency is expected in the outcomes of the assessment of stock status evaluation.

Finally, the Commission Decision states that "the extent to which GES has been achieved shall be expressed for each area assessed as follows: (a) the populations assessed, the values achieved for each criterion and whether the levels for D3C1 and D3C2 and the threshold values for D3C3 have been achieved, and the overall status of the population on the basis of criteria integration rules agreed at Union level" (EU-COM, 2017). The criteria integration rules defined at the Union level are not yet specified, including in relation to methods of integration from assessment areas to subregional and regional levels (Zampoukas et al., 2014). Again, if no common agreement on the approach is achieved, it will prevent a consistent GES assessment at the Mediterranean level.

CONCLUSIONS

We analyzed and compared the approaches applied by EU Mediterranean member states in the early phases of the implementation of the MSFD in relation to commercial fisheries. What emerged is a lack of consistency in the selection of stocks, application of reference points, and definition of GES and ETs. MSFD criteria and methodological standards were applied with different interpretations across member states, showing that subregional and regional coordination was not effectively enforced. Moreover, only a partial use of potentially available data for GES assessment was identified, while new frameworks in relation to data collection (both at the EU and GFCM levels) suggest an increase in data availability for GES assessment for the future.

The recently reformed Commission Decision on criteria and methodological standards for GES (EU-COM) supports a more coherent approach to be applied in the forthcoming assessment of GES, which would also foster better coherence with the reformed CFP. However, several elements that could determine the uneven application of MSFD are still not completely clarified, particularly stock selection and criteria for the integration of GES assessment from stocks to assessment areas and subregions, as well as the methodological approach to the use of secondary indicators. The definition of a common, regional, and subregional approach is given to relevant regional and subregional cooperation bodies. Thus, their capability of defining and agreeing on a common, structured approach will be essential to ensure an even application of the MSFD in relation to commercial fisheries. However, since the next GES assessment will need to be carried out by 2018, there is an urgent need to implement such a process in the short term, and we hope this research will add to this framework.

Achieving consistency in MSFD implementation should also foster an improvement of stocks status in the Mediterranean region, which is lagging behind in comparison to the Northern-Atlantic countries in terms of tangible results (Cardinale and Scarcella, 2017). Ensuring that MSFD and CFP policies will be applied with the needed consistency at the pan-European level requires increased cooperation among scientists and member states from Mediterranean countries within GFCM and the Barcelona Convention, and collaboration between these institutions, ICES, other Regional Sea Conventions, and STECF/SGMED (Freire-Gibb et al., 2014; van Leeuwen et al., 2014).

Current data of F (Cardinale and Scarcella, 2017) suggest a low probability of reaching GES in the short term in the Mediterranean. Beyond the technical issues associated with GES definition and assessment, reaching this goal will also need better coordination among member states and other countries in relation to the definition of the programmers of measures, since the Mediterranean Sea is typically characterized by shared stocks (e.g., in the Adriatic Sea and Strait of Sicily). This is another complexity that adds to the multispecificity of fishing activities, the relevance of small-scale fisheries, and the political diversity of the area.

AUTHOR CONTRIBUTIONS

SR conceived the work. SR, PB, and TF collected data. TF and SR performed the analysis. All the authors wrote and revised the paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2017.00316/full#supplementary-material

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Following an investigation by the European Commission's Joint Research Center, it was found that Dr. Giacomo Chato Osio meets the criteria to be listed as an author on this manuscript. The authorship list is therefore updated to be:

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