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Année universitaire : 2023-2024 Spécialité : Ingénieur agronome Spécialisation (et option éventuelle) : Sciences Halieutiques et Aquacoles (Ressources et Ecosystèmes Aquatiques)	**Mémoire de fin d'études** ☒ d'ingénieur de l'Institut Agro Rennes-Angers (Institut national d'enseignement supérieur pour l'agriculture, l'alimentation et l'environnement) ☐ de master de l'Institut Agro Rennes-Angers (Institut national d'enseignement supérieur pour l'agriculture, l'alimentation et l'environnement) ☐ de l'Institut Agro Montpellier (étudiant arrivé en M2) ☐ d'un autre établissement (étudiant arrivé en M2)

Evaluating the impacts of management scenarios in the Mediterranean Sea using an ecosystem-based and multi-fleet modeling approach

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Soutenu à Rennes le 11/09/2024

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Acknowledgements

I would like to express my deepest gratitude to the entire work team, both osmosers and non-osmosers, for their kindness and for welcoming me so warmly into the lab, making this internship a truly memorable experience. In particular, I owe a huge thank you to Clea, whose kindness, support, patience, pedagogy, and dedication made her the best supervisor I could ever ask for. Without her, I would not have learned as much. Thank you, Clea, for enriching this internship and for the countless hours you spent helping me.

I would also like to express my sincere thanks to Yunne for making this opportunity possible, for her wise and brilliant advice, and for the enriching conversations that have always inspired me so much.

Alongside Clea and Yunne, a big thank you to Marine, Ignacio, Daniela, Adrien, Nicolas, Bruno, Fabien, and Ricardo for being such a sweet and dynamic team; it was a pleasure to work and discuss with you all.

I am also grateful for the interns with whom I shared this journey, who made this experience truly memorable. A special mention goes to Talia, the friend I did not expect to make during these few months.

I also want to extend my gratitude to my teachers at L'Institut Agro Rennes Angers for their valuable instruction during all my studies, and to the school for making this internship possible.

Finally, as this thesis marks the end of my studies, I would like to thank my family and all my friends from home, Southern France, Northern France, and abroad, both life-long and newly-arrived, who have supported me throughout these five years, even if some may still not know what I do besides "working on fish." I am deeply grateful for always being surrounded by such wonderful people in both the best and the most challenging times. Thank you to everyone who made this journey even more enjoyable.

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Glossary

CBD : Convention on Biological Diversity

EEZ : Economic Exclusive Zone

FPA : Fully Protected Area

GFCM : General Fisheries Commission for the Mediterranean

GSA : Geographical Sub-Area

MPA : Marine Protected Area

MSY : Maximum Sustainable Yield

PPA : Partially Protected Area

SAU : Sea Around Us

STECF : Scientific, Technical and Economic Committee for Fisheries

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Introduction

Accounting for approximately 17,000 marine species (Micheli et al., 2013) - representing 4% of identified marine species concentrated in less than 1% of the global ocean area - the Mediterranean Sea is a hotspot of biodiversity (Coll et al., 2010). It also supports the livelihood of its twenty-two bordering states, with 743,100 tons of species fished in 2020, representing a value of 2.7 billion dollars (FAO, 2022). On average, 1 out of 1,000 residents is a fisher, a ratio reaching 1/100 in some countries. Mediterranean fisheries are highly diversified in terms of species targeted and gears used. Small-scale vessels make up over 80% of the fishing fleet, representing around 60% of the fishing sector employees, though producing only 15% of the total catch (FAO, 2022). The Mediterranean Sea's biodiversity is threatened by many anthropogenic pressures such as habitat degradation, climate change, pollution, eutrophication and aquaculture, (Coll et al., 2010; Lotze et al., 2006; Micheli et al., 2013), the most impactful being overexploitation (FAO, 2023a). Indeed, the current fishing mortality is more than twice that corresponding to the maximum sustainable yield (MSY) and 58% of commercial stocks are fished outside biologically sustainable limits (FAO, 2023b). There is no doubt industrial fishing plays a major role in the unhealthy state of stocks (Cavallé et al., 2020).
According to Cardinale et al. (2017), this is due to the ineffectiveness of fisheries management, notably to control fishing mortality, as well as the non-adherence to scientific advice, catches being much above recommendation levels.

In order to protect biodiversity, Marine Protected Areas (MPAs) are tools that are being wildly promoted and applied. IUCN has defined an MPA as « any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part of all the enclosed environment » (Kelleher, 1999). MPAs that produce the largest amount of benefits have been shown to be no-take, well-enforced, old (>10 years), large (>100 km^2) and isolated by deep water or sand (Claudet et al., 2008; Edgar et al., 2014). If well implemented and enforced (Gill et al., 2017), MPAs can increase the abundance, biomass and diversity of species (Lester et al., 2009) and can constitute a refuge for vulnerable species notably individuals with large size and high trophic level (Boulanger et al., 2021) or migratory species when designed on migratory routes (Boerder et al., 2019). Furthermore, fisheries can benefit as well from MPAs due to the spillover of juveniles, subadult and adult biomass from the reserve towards outside areas, increasing fishable biomass (Di Lorenzo et al., 2016). Belharet et al. (2020) showed that doubling the size of fully protected areas over fishable areas within an existing network of MPAs would lead to benefits for three ecologically and economically important coastal fish species. Eventually, well designed and managed MPAs could also mitigate the effects of climate change (Roberts et al., 2017).

During the COP of the Convention on Biological Diversity (CBD) in 2010, members of the United Nations agreed on covering up to 10% of marine areas with MPAs by 2020 (Aichi target 11) (CBD, 2010), which was revised in 2022 and fixed to 30% by 2030. However, only 6.01% of the Mediterranean Sea is covered by MPAs, composed of 1,062 MPAs, 95% of which do not have stronger regulations than unprotected areas (Claudet et al., 2020; Costello & Ballantine, 2015). Indeed, only 0.23% of the basin is protected from the destructive exploitation of fishing grounds and only 0.06% are no-take areas, while such areas have been shown to be crucial for the replenishment of fish stocks (Sala & Giakoumi, 2018). Consequently, it is crucial to carry out further studies assessing the impacts of different scenarios of MPAs on marine ecosystems as well as on fisheries economy in order to strategically implement a network of MPAs. Management measures must account for the diversity of species and fisheries in the

Mediterranean Sea to assess their impacts more precisely.

In addition to spatial management measures, the European Commission proposed the reduction of fishing effort as a regulation measure (European Commission, 2003) and some action plans are starting to be implemented in the Mediterranean Sea. The fishing mortality in 2023 was 2.13 greater than the fishing mortality target at the maximum sustainable yield (FMSY) (FAO, 2023a). In this context, the West-Med Plan (European Parliament and Council, 2019) has been set, which aims to reduce the fishing effort of bottom trawlers in the Western Mediterranean Sea, due to their destructive impact on marine ecosystems (FAO, 2023b).

Ecosystem models are key tools for testing such management actions. The model used in this study is OSMOSE-MED, a spatialized individual-based trophic model that takes into account 95% of the declared catch of the Mediterranean Sea and enables to work at the scale of the entire Mediterranean basin with a relatively high resolution (20 km x 20 km) (Moullec, Velez, et al., 2019). We updated the model with a more realistic representation of Mediterranean fisheries, accounting for the spatial distribution of fishing effort (Abello et al., in prep), the diversity of fleets and gears (FAO, 2023a) as well as the implementation of fleet-specific management measures.

In this study, we aim to assess the impacts of different scenarios of spatial and non-spatial management measures on Mediterranean fisheries and ecosystem, in terms of biomass, catch and economic gains. Eventually, the objective is to identify the scenario that allows the best trade-off between biodiversity conservation and fisheries profitability.

Material and method

1. The modeling chain: the multi-fleet OSMOSE-MED model

1.1. The OSMOSE model

In this study, the different fishing and management scenarios tested were simulated with the OSMOSE model (Object-oriented Simulator of Marine ecOSystEms), a spatialized individual-based trophic model developed by Shin and Cury (2001). OSMOSE aims to model the life cycle of species of fish and macroinvertebrates from egg to adult stage, through processes like growth, reproduction, predation, natural and fishing mortalities. Each school is modeled as a single « super-individual », that is defined with unique length, age, diet and spatial position in two dimensions (Shin & Cury, 2004). Those super-individuals interact through predation which, as a main assumption of the OSMOSE model, is considered opportunistic and size-based (Shin & Cury, 2001, 2004). Each fish can be prey or predator to another fish depending on maximum/minimum size ratios (Travers et al., 2009). At each time step, a predation efficiency rate is estimated, which determines the growth, starvation and reproduction rates (occurring for fish with a length greater than the sexual maturity length). The other condition is the spatial accessibility of prey to predators, defined horizontally by species distribution maps and vertically through the prey-predator accessibility matrix. At each step time, schools move from one cell to an adjacent one or remain in the same cell following a random walk process (Shin & Cury, 2004; Travers-Trolet et al., 2014). The growth and mortality functions are deterministic, therefore, the inherent stochasticity of the model resides in the order at which fish schools interact and their movement in their habitat.

1.2. The Mediterranean configuration: Osmose-Med

We used OSMOSE-MED, the Mediterranean Sea configuration of the OSMOSE model, which takes into account 97 marine species (82 fish, 10 cephalopods and 5 crustaceans), representing 95% of the declared catches for the period 2006-2013, at a spatial-temporal resolution (6229 cells of 20x20 km, 15-day step) that is relatively high for a basin-wide application (the Mediterranean basin, from 26.9°N to 46.3°N in latitude and 5.6°W to 253 36.1°E in longitude) (Moullec, Velez, et al., 2019). The end-to-end model OSMOSE-MED was built from the coupling of the high trophic level model OSMOSE with the hydro-dynamic model CNRM-RCSM4 (Sevault et al., 2014) and the biogeochemical low trophic model Eco3M-S (Auger et al., 2011) (Figure 1). Species distribution maps, obtained from niche modeling are set as inputs to the model.

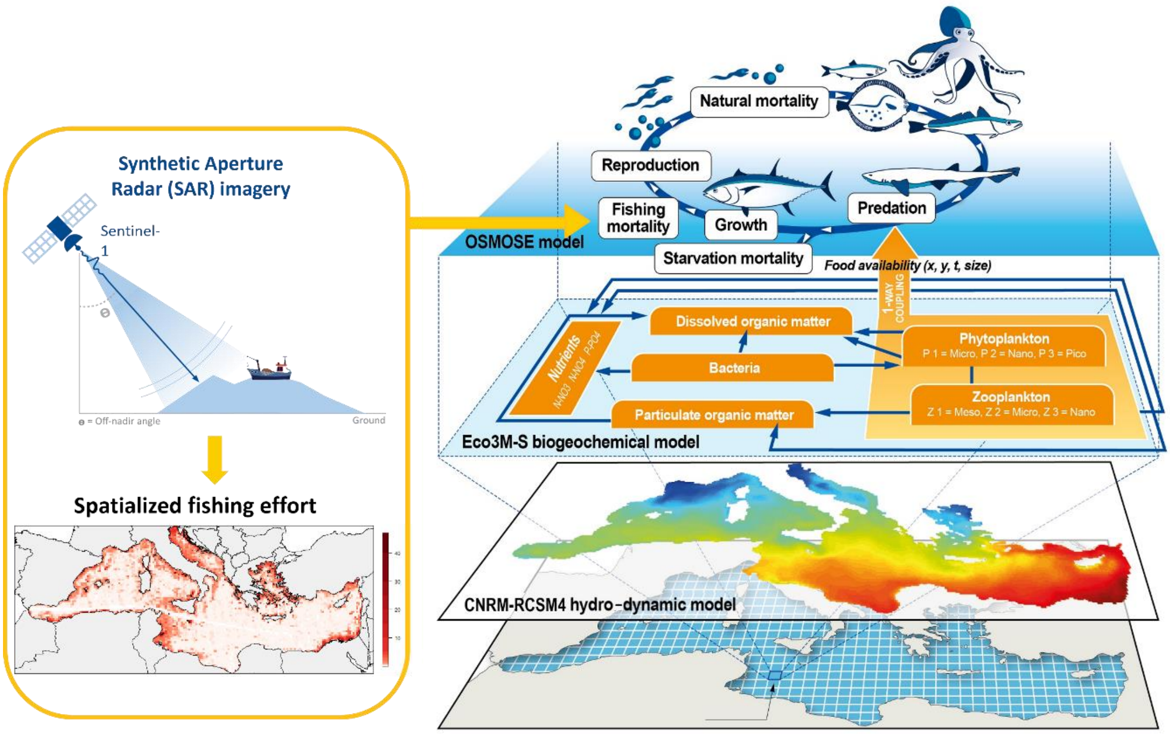


Figure 1: Conceptual representation of the OSMOSE-MED model (from Abello et al., in prep; Moullec et al., 2019).

The model was run for 100 years (spin-up), in order to reach a steady state. We then implemented different management scenarios and let the model run for 30 years to reach a new stable state, and only the following 30 years were saved as outputs and analyzed. As the model is stochastic, 10 replicates were run and averaged for each simulation as in (Moullec, Velez, et al., 2019). All simulations were run on DATARMOR, the high-performance computing platform of the French Research Institute for Marine Exploitation (IFREMER) at the 'Pôle de Calcul et de Données Marines'.

1.3. The novelty of this model version: fleet-specific fishing effort

Initially in OSMOSE-MED, fishing effort was distributed homogeneously across the basin (Moullec, Velez, et al., 2019). Using satellite imagery, it was spatialized in the following version of the model (Abello et al., in prep), leading to more accurate results and projections. The Mediterranean Sea is characterized by a diversity of fleets and fishing gears (FAO, 2023a), 82% being small-scale fisheries. Management measures may not impact all fisheries in the same way, therefore, for a better assessment, we distributed the total fishing effort by fleet. Due to the highly mixed nature of Mediterranean fisheries, twenty-one fleets were modeled but for an easier understanding of the results, the outputs were aggregated into six major fleets (Table 1). For each fleet, we defined a fishing selectivity curve, based on the scientific literature, as well as a catchability matrix for each modeled species.

To account for the spatial distribution of industrial fishing vessels (> 12 m), we used the Global Fishing Watch dataset of satellite detections (SAR) over the period 2017-2021 (Paolo et al., 2024) representing the geographical positioning of industrial fishing vessels, classified by gear category via coupling with AIS data and deep-learning. We were able to refine the assignment of vessels to a given type of fishing gear by coupling this dataset with the GFCM Mediterranean fleet register. For detections of fishing vessels not assigned to a given gear type (which are numerous, particularly in the southern Mediterranean, due to less accurate AIS data), we chose to randomly assign them to a gear category according to the proportions indicated in the latest GFCM report (FAO, 2023).

For the spatial distribution of artisanal fleets (< 12 m), we considered that the fishery was coastal (only present in the 1st cell of the model along the coast with a resolution of 20 x 20 km²) and we distributed it according to the number of artisanal vessels per country recorded by the GFCM (FAO, 2023).

The OSMOSE-MED model was fitted to catch data by gear type and species by EEZ from the Sea Around Us Project. After incorporating the multi-fleet dimension, the model parameters (in particular, the larval mortality parameter) were adjusted manually to better fit the model to the data.

Table 1: The 21 modeled fleets and the aggregation for the analysis of outputs. The names can directly refer to the gears used as well as the length of the vessels.

Fleets names	Aggregated fleets names
Artisanal small hooks Artisanal large hooks Artisanal cephalopod hooks Artisanal small nets Artisanal large nets Mixed small artisanal gear Mixed medium artisanal gear Mixed large artisanal gear Artisanal hooks swordfish	Artisanal
Bottom trawl small Bottom trawl medium Bottom trawl large Shrimp trawl	Bottom trawlers
Hooks and lines Swordfish longliners	Longliners
Industrial others small Industrial others large Industrial others very large	Other industrial fleets and unknown

Purse seine large pelagic Purse seine small pelagic	Purse seiners and pelagic trawlers
Tuna purse seine	Tuna purse seiners

2. Management scenarios tested

2.1. Spatialized management measure: Marine Protected Areas

Many MPAs with a wide range of level of protection exist worldwide from no-take areas (reserves), banning any type of extraction to multiple-use areas where some activities persist (Grorud-Colvert et al., 2021; Horta e Costa et al., 2016).

In this study, we tested three different spatial management scenarios:

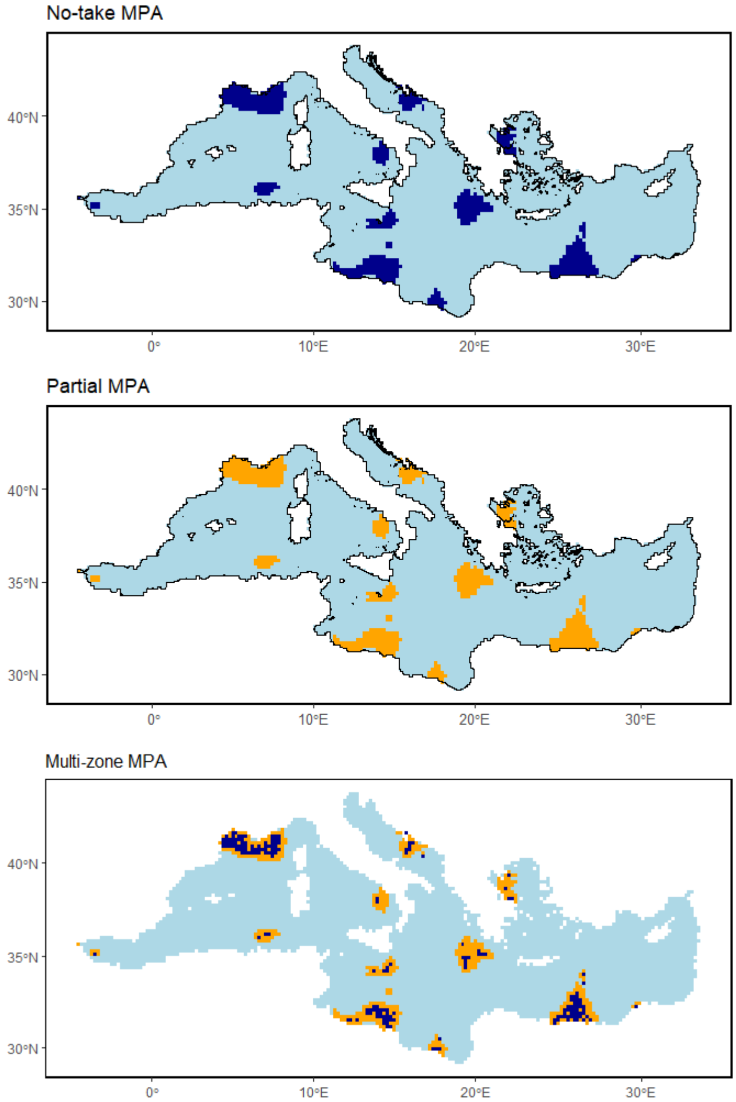


Figure 2: Scenarios of networks of Marine Protected Areas for a 10% coverage, tested in this study based on (Mazor et al., 2014). Blue: ban for all fleets. Orange: ban for highly impactful gears only (here, bottom and shrimp trawls).

(1) Fully protected areas (FPAs) or 'No-take': complete ban for all fleets.

It is the strictest of our scenarios: MPAs are fully protected from fishing. Many studies show that this is the most efficient way to protect biodiversity and that no-take areas help increase biomass, species richness and mean length (Costello & Ballantine, 2015; Edgar et al., 2014; Lester et al., 2009; Sala & Giakoumi, 2018).

(2) Partially protected areas (PPAs): ban for high impact fleets only (i.e., demersal trawlers)

No-take MPAs, despite their efficiency, are difficult to establish and can generate negative social impacts (Gill et al., 2024). Partially protected areas (PPAs), even though they are less efficient than no-take areas from a conservation perspective, can still confer ecological benefits and appear as a good alternative for fisheries sustainability (Sala & Giakoumi, 2018; Zupan et al., 2018). We thus decided to simulate a less restrictive MPA management scenario, in which only the most destructive fleets (FAO, 2023a) are banned from the managed area. We considered demersal trawlers as the most impactful gear types (in our model, bottom trawlers and shrimp trawlers) (Quemper et al., 2024). This measure is supported by the European Commission, calling for a ban on mobile bottom fishing in all MPAs by 2030 (European Parliament, 2023).

(3) Multi-zone MPAs: ban for all the fleets in one third of the MPA (blue) and ban for bottom and shrimp trawls in the entire MPA (orange).

This scenario refers to « multi-use » areas. They were also proven to increase biomass of fish and to be efficient mostly in overexploited areas (Gill et al., 2024). Given the state of the Mediterranean Sea, we decided to test this scenario as well. The Great Barrier Reef Marine Park has been reported as the best example of this « zoning » management (Day et al., 2019). Some closer examples can be found in the Northwestern Mediterranean Sea, such as in the Cerbère-Banyuls, Cap de Creus and Medes Islands MPAs (Corrales et al., 2020). The 1/3 ratio was selected based on the targets of the CBD for 2030, 30% of MPAs among which one third must be fully protected.

The placement of the MPAs for all the scenarios was chosen based on the study of Abello et al. (in prep.) in which various MPA scenarios, both random and based on ecological and economic criteria were tested, including one from Mazor et al. (2014), which provided the best results in terms of both conservation and fisheries benefits. The selection of areas in this scenario was done using an algorithm computing the best trade-off between protecting 10% of the distribution area of the 77 endangered marine species and minimizing the impact on fisheries.

Each MPA network was simulated to cover 5%, 10%, 15%, 20%, 25%, and 30% of the Mediterranean basin in order to study the incremental changes in biomass and catch. Due to space constraints, the plots display the results for 10% and 30% coverages only.

- Scenarios of fishing effort redistribution

After the implementation of an MPA, fishing effort is redistributed outside of this area. Based on Hoos et al. (2019) and Abello et al. (in prep), two strategies of redistribution were modeled: a redistribution by geographical sub-area (GSA) proportional to the effort before MPAs and a uniform redistribution by GSA.

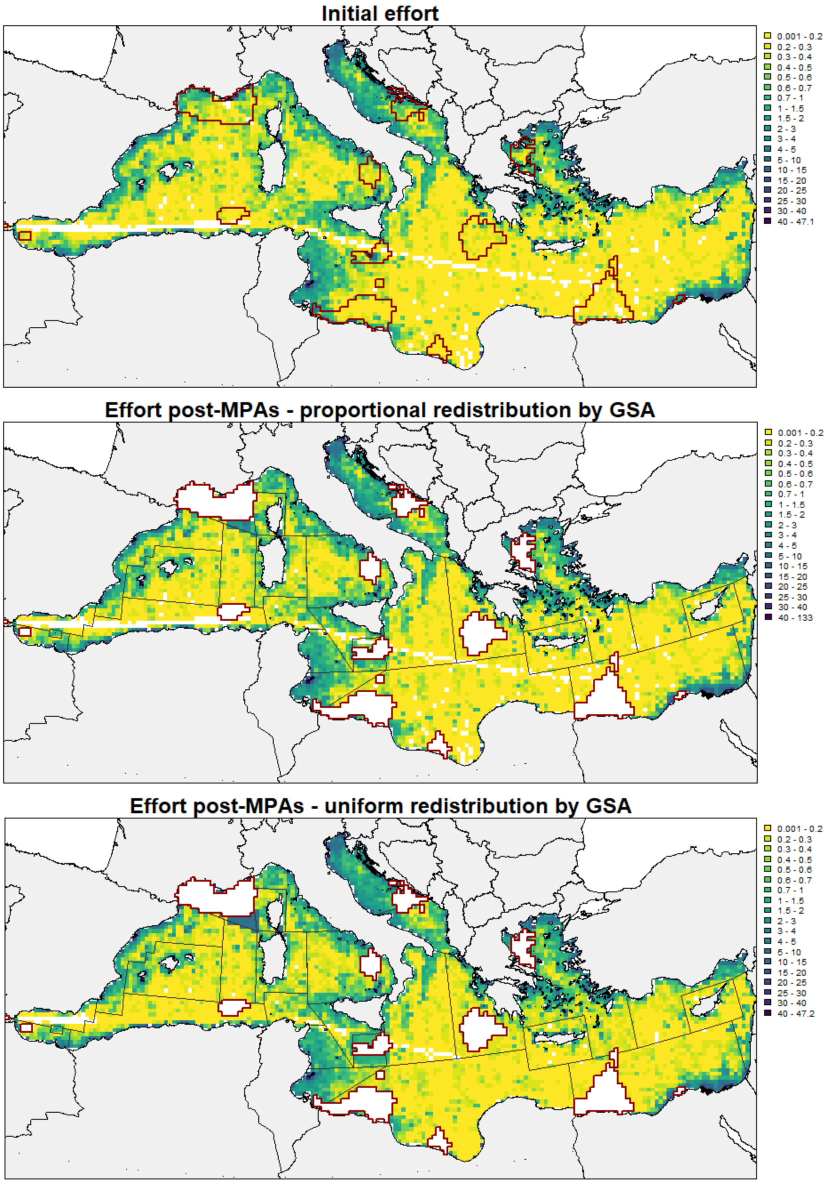


Figure 3: Distribution of the initial effort, a proportional redistribution by GSA and a uniform redistribution of fishing effort after the implementation of MPAs (areas filled with white and outlined in red) (Abello et al., in prep).

In the Uniform strategy by GSA, fishing effort is redistributed uniformly within each GSA.
In the Proportional strategy by GSA, fishing effort is redistributed proportionally to the areas in which there already was a fishing effort in the same GSA before the establishment of an MPA.
Both redistribution strategies clearly have limitations. The uniform one likely overestimates the redistribution capacity of fleets, as some distance from home ports would be too great for fleets to still be sustainable. The proportional one, on the contrary, may underestimate the ability of fleets to fish in new areas, especially fleets that have a limited initial distribution, such as artisanal fleets.
Assuming that the reality lies somewhere in between both strategies, we thus decided to average the simulation results obtained from both fishing effort redistribution scenarios.

2.2. Non-spatialized management measure: fishing effort reduction

Many studies demonstrate that lowering the total fishing mortality in the Mediterranean Sea would lead to an increase in total fish biomass as well as in catch of high trophic level species (Belharet et al., 2020; Moullec et al., 2023). Furthermore, in different areas of the Mediterranean Sea, lowering the fishing effort of bottom trawlers would enhance the biomass of demersal species and predators (Erauskin-Extramiana et al., 2024; Fouzai et al., 2012; Moullec et al., 2023; Sgardeli et al., 2022).

In line with the goals of fishing effort reduction plans (European Commission, 2003; European Parliament and Council, 2019), we conceived a scenario of fishing mortality reduction. In OSMOSE, the relation between fishing mortality and fishing effort is considered as linear, following this formula:

$$F = q \times E$$

where F is the fishing mortality rate, q the catchability and E the fishing effort.
Thus, a fishing mortality reduction can serve as a proxy of a reduction in fishing effort. The new fishing mortality F' for one species can therefore be computed according to the following formula:

$$F' = (1 - \alpha) \times F_{current}$$

where $\alpha \in \{0.05, 0.10, 0.15, 0.20, 0.25, 0.30\}$, and $F_{current}$ corresponds to the current fishing mortality of a given species.
The values of the multiplier α were chosen based on the literature and the targets of the West-Med Plan that sets a reduction of bottom trawlers fishing effort in the Western Mediterranean Sea by 30% by 2025.

3. Indicators

To assess the impact of management measures on Mediterranean ecosystems and fleets, different indicators were considered. Biomass and catch changes were computed from the outputs of the model and analyzed across various aggregation levels, including by species functional groups, by commercial interest, and by fleets. OSMOSE-MED can generate spatialized outputs, which enabled us to plot those changes depending on the proportion of MPA coverage within GSA.

Catches are expressed in tons, but also in value, hereafter referred to as landed value, in order to assess the economic impact of fishing managements measures on Mediterranean fisheries. Landed value is not an output of the model but was calculated a posteriori by species, by fleet and by GSA.
To do so, data from the Sea Around Us project and from the Scientific, Technical and Economic Committee for Fisheries of the European Commission (STECF) was collected.
from 2006 to 2013, as the model is based on catch data from this period. Data was homogenized; gear, species and country codes were assigned to names common to both datasets. From gear types and vessel length, data was aggregated into fleets. In the SAU database, data was initially organized by Exclusive Economic Zones (EEZ), whereas for STECF data was available by FAO statistical divisions. As closely as possible, data areas were matched with the Geographical Sub-Areas division of the Mediterranean Sea to enable a comparison between both datasets. Both datasets were then compared and filtered in order to create the most reliable

and complete price database. Indeed, STECF data is based on declarative data from only Mediterranean countries in the European Union, thus most likely underestimating the total tonnage. On the other hand, the Sea Around Us database embeds all Mediterranean countries, but is partly based on estimations and therefore can be inaccurate in areas where data is scarce. Catches in value and tons were then divided in order to calculate the price per kilo (€/kg) by species, by fleet, by GSA, by year, by fishing entity (country of the fishing vessels) and by source (SAU or STECF), and finally averaged between years.

To create the most complete and reliable database, a comparison between both datasets was then undertaken for common countries, GSAs, fleets and species (Table 2).

Table 2: Filtering process of catch data collected from SAU and STECF for the comparison of both datasets.

Step	Description
1. Filtering by common countries	Extract data with fishing countries common to both datasets
2. Filtering by common GSAs	From the common countries dataset, extract data in GSAs common to each country in both datasets
3. Filtering by common fleets	From the common countries and common GSAs dataset, extract data with fleets common to each country x GSA in both datasets
4. Filtering by common species	From the common countries, common GSAs and common fleets dataset, extract data with species common to each country x GSA x fleet in both datasets

The resulting filtered common data (4) was averaged and then completed with all the filtered data coming from only one source. The standard deviation for each price corresponding to a species x fleet x fishing country x GSA combination was computed, and each price value above this threshold was removed from the database in order to remove outliers. A final database was created by averaging the price by species, fleet, GSA and fishing entity.

- Classification of species of commercial interest:

A classification by species functional group enables to analyze the ecological benefits of MPAs but it is less informative about the potential impact on fisheries. Therefore, to complete this analysis, a classification of the commercial interest of species was adopted (Appendix I). It is based on the catch data collected from the SAU and STECF as described above. The commercial interest is declined in five categories, based on threshold of landed value computed from the existing and afterwards compared to different sources for validation (Claudet et al., 2020; Froese & Pauly, 2024; Guidetti et al., 2014):

- NC: non-commercial
- LC: low commercial
- C: medium commercial
- HC_small_pelagics: highly commercial small pelagic species
- HC_others: highly commercial species other than small pelagic species

This classification intends to better identify the benefits and drawbacks of management measures on fisheries.

Results

1. Analysis by total biomass, catch and landed value

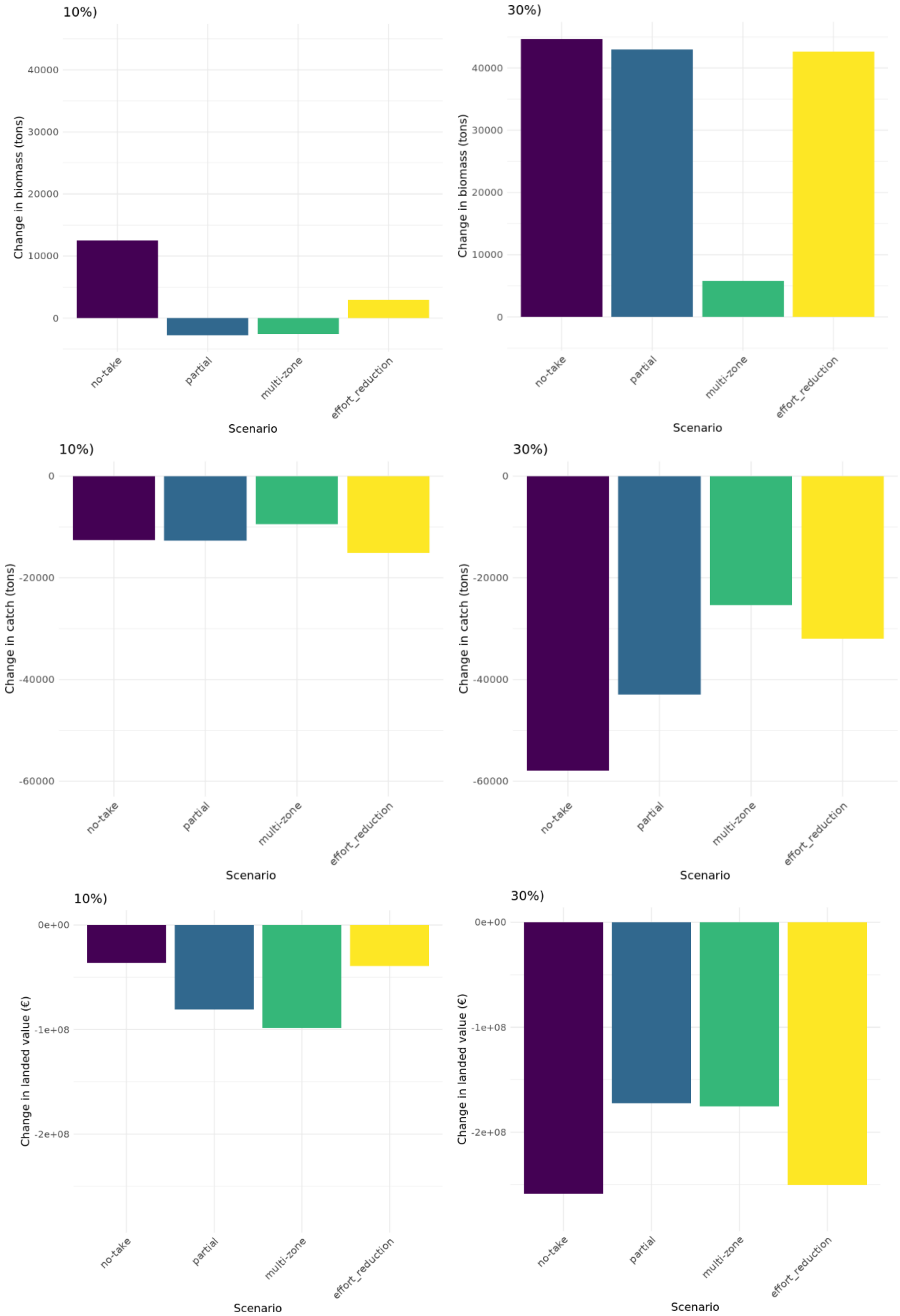


Figure 4: Change in biomass (tons), catch (tons) and landed value (€) by scenario for 10%

MPA coverage (left) and 30 % MPA coverage (right).

The most efficient scenario in terms of gain in biomass is the no-take scenario (S1), for both MPA coverages (10% and 30%) (Figure 4). Indeed, implementing a 10% MPA network would increase fish biomass ten times more than reducing the fishing effort by 10%. Consequently, the no-take appears to provide better protection for biodiversity with a 10% MPA coverage. As a matter of course, catches (in tons) decrease more under a no-take scenario compared to less restrictive scenarios, especially with a larger MPA coverage (30%). Specifically, they decrease by nearly 60,000 tons compared to approximately 43,000 tons under a PPA scenario (S2), to 25,000 tons under a multi-zone scenario (S3) and to 32,000 tons under an effort reduction scenario (S4).

Implementing a 30% PPA network (S2) would result in an increase in biomass nearly as important as that under a no-take scenario, reaching almost 45,000 tons while saving €100 million in landed value. A 30% reduction in fishing effort (S4) would trigger a total biomass change close to a 30% PPA network (S2) as well as a lower loss in catch but a €70 million greater economic loss. Similarly, a reduction in fishing effort would also trigger a positive biomass change even with a 10% reduction. Nevertheless, the loss in landed value is close to that observed under a no-take scenario, reaching ca. €250 million. Therefore, a PPA network scenario might be less strict for the fisheries (Gill et al., 2024).

The multi-zone scenario (S3) seems to be the least effective scenario in terms of biomass. Here, whereas catch change is the smallest, the biomass increase is approximately seven times lower compared to the other scenarios approaching only 6,000 tons with a 30% MPA coverage. Some studies indeed show that multi-zone MPAs are less efficient at enhancing fish biomass than no-take MPAs (Sala & Giakoumi, 2018). However, the loss in catch volume is the lowest across the scenarios and 18,000 tons lower than that under a PPA scenario (S2) with a 30% MPA coverage even though their economic loss is similar.

In a 10% MPA network scenario, some scenarios produce a negative yet very low biomass change. Conclusions on the unefficiency of the PPA (S2) and multizone (S3) based on these results could however overlook important trends. This underlines the importance of studying the results by functional groups.

2. Analysis by functional groups

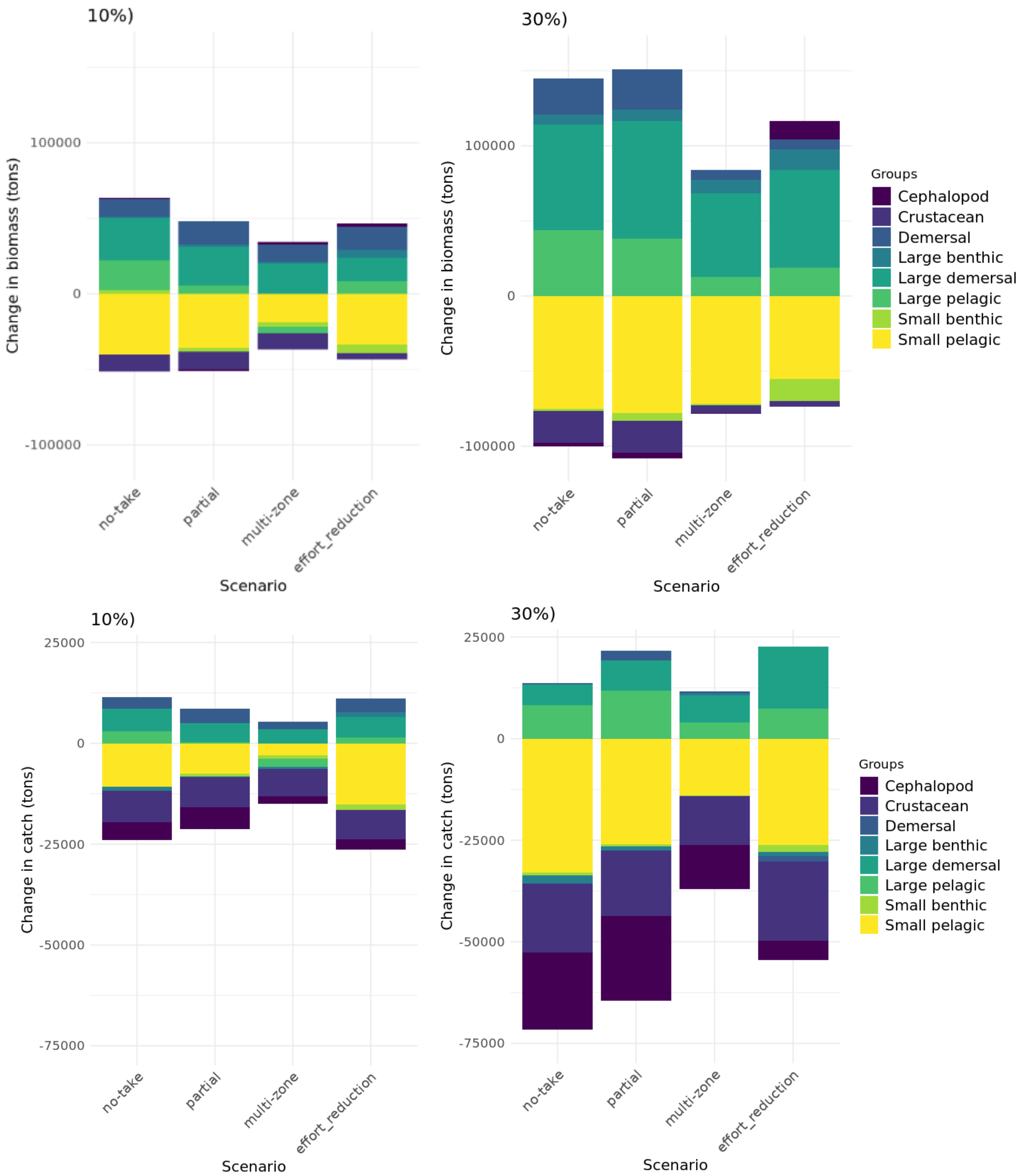


Figure 5: Change in biomass (tons) and in catch (tons) by group and by scenario for 10 % MPA coverage (left) and 30 % MPA coverage (right).

Looking at the group scale, the impacts of management measures vary from one group of species to another (Figure 5). The groups always benefiting from management scenarios in terms of biomass, regardless of the intensity of the measure implemented, are large demersal, large pelagic (excepted in a multi-zone scenario at 10% coverage) and large benthic species. On the contrary, the groups negatively impacted in all scenarios are small pelagic species, crustaceans and cephalopods (excepted in an effort reduction scenario). This is consistent with studies showing that the species benefiting the most from MPAs are large species, mostly predators of high trophic levels, initially targeted by fishing (Edgar et al., 2014; Guidetti et al., 2014; Rojo et al., 2021). Conversely, the biomass of low trophic species like small pelagics declines due to the increase of predation pressure by top-down control (Albouy et al., 2010). This explains the slightly negative total biomass changes observed under a PPA scenario (S2) and multizone scenario (S3) (Figure 4).

All the mentioned groups show the same trend regarding catch: those having a positive biomass change also have a positive catch change and conversely. As a matter of course, catches (in tons) decrease more under a no-take scenario (S1) across all fish groups compared to less restrictive scenarios, especially with a larger MPA coverage (30%).
However, despite an increase in cephalopod biomass under an effort reduction scenario (S4), their catches decrease as for MPA scenarios (Figure 5). Once again close to the PPA scenario (S2) in terms of biomass change but this time as well as in catch change, the effort reduction scenario (S4) is the only one benefiting cephalopods, besides a very low increase in biomass for 10% multi-zone MPA scenario (S3). On the one hand, this might be due to trophic cascades inherent to MPAs which foster predators, therefore affecting cephalopods with a low trophic level. On the other hand, this could also be due to the fact that the major fleet targeting cephalopods are bottom trawlers, which suffer from spatial squeeze in all scenarios, causing a decrease in catch.

The multi-zone scenario (S3) triggered the lowest total biomass change and when it comes to group changes, they remain the lowest as well, for the positive one. Thus, the decrease of small pelagic species' biomass is around 70,000 tons for all scenarios, largely driven by the decline in European anchovy *Engraulis encrasicolus* (68% on average). Even though looking at catches, the loss is around twice lower than for the PPA scenario (S2) and more than twice lower than for the no-take scenario (S1). This may be due to a less significant increase in the biomass of large pelagic species, and a low predation pressure.

As a result, the PPA (S2) and the fishing effort reduction scenarios (S4) appear to be more suitable to address the trade-offs between biomass and catches as the results are close to the no-take scenario (S1).

3. Analysis by commercial interest

Figure 6: Change in biomass, in catch (tons) and landed value (€) by commercial interest and by scenario in a 10% MPA coverage (left) and a 30% MPA coverage (right). C: commercial. HC_others: highly commercial species apart from small pelagic species. HC_small_pelagics:

highly commercial small pelagic species. LC: low commercial interest. NC: non-commercial.

These results aggregated by commercial interest show that regardless of the scenario, commercial species and highly commercial other species experience an increase in biomass, reaching a maximum of 60,000 tons (+5%) and 90,000 tons (+15%) respectively in a 30% effort reduction scenario (S4) (Figure 6).
Contrary to the effort reduction scenario (S4), MPA scenarios enable to increase the biomass of low-commercial species, and the no-take scenario (S1) under 30% MPA coverage is the only scenario benefiting non-commercial species, although slightly.
On the other hand, highly commercial small pelagics species decline in biomass in all scenarios, in line with the decrease observed in the results above.

Therefore, even though MPAs do not lead to large changes in total biomass, they enable to protect and rebuild commercial fish stocks.
However, these results may affect fleets differently from one another.

4. Analysis by fleets

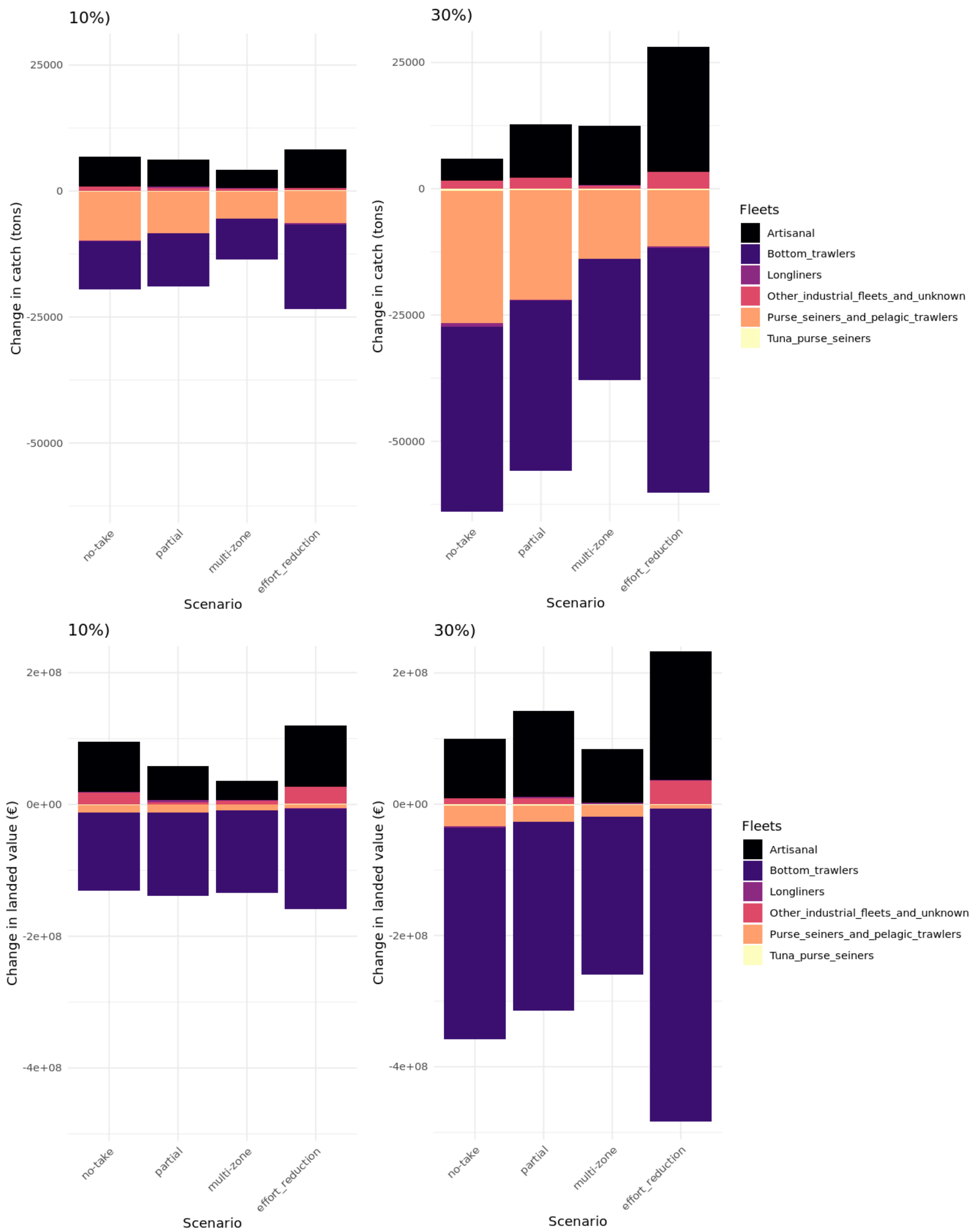


Figure 7: Change in catch (tons) and in landed value (€) by fleet and by scenario for 10 % MPA coverage (left) and 30 % MPA coverage (right).

Regarding catch change by fleets, artisanal fleets consistently benefit from management measures no matter the scenario (Figure 7). Although the no-take scenario (S1) is the only restrictive scenario for them, artisanal fisheries catches still increase, yet more than twice less than in the PPA scenario (S2) and three times less than in the multi-zone scenario (S3), with a 30% MPA network. Even when restricted, artisanal fleets benefit from MPAs through spill-over effect (Di Lorenzo et al., 2016, 2020), due to the increase in biomass of their target species as well as of larger fish, mainly highly commercial large pelagic and large demersal species, such as the Greater amberjack *Seriola dumerili*, the European seabass *Dicentrarchus labrax*, the European hake *Merluccius merluccius* and the common dentex *Dentex dentex*. Besides artisanal fisheries, some industrial fisheries (see 'other industrial fleets and unknown' category, Figure 7) seem to also benefit from MPA spillover. Moreover, the most effective scenario for artisanal fleets is the fishing effort reduction (S4), generating an increase of 25,000 tons in catch (+ 10%). As shown previously (Figure 5), large pelagic and large demersal species are the only groups increasing in terms of catch, with the largest rise in large demersal biomass out of all the scenarios. Those groups are in fact heavily targeted by artisanal fleets. .

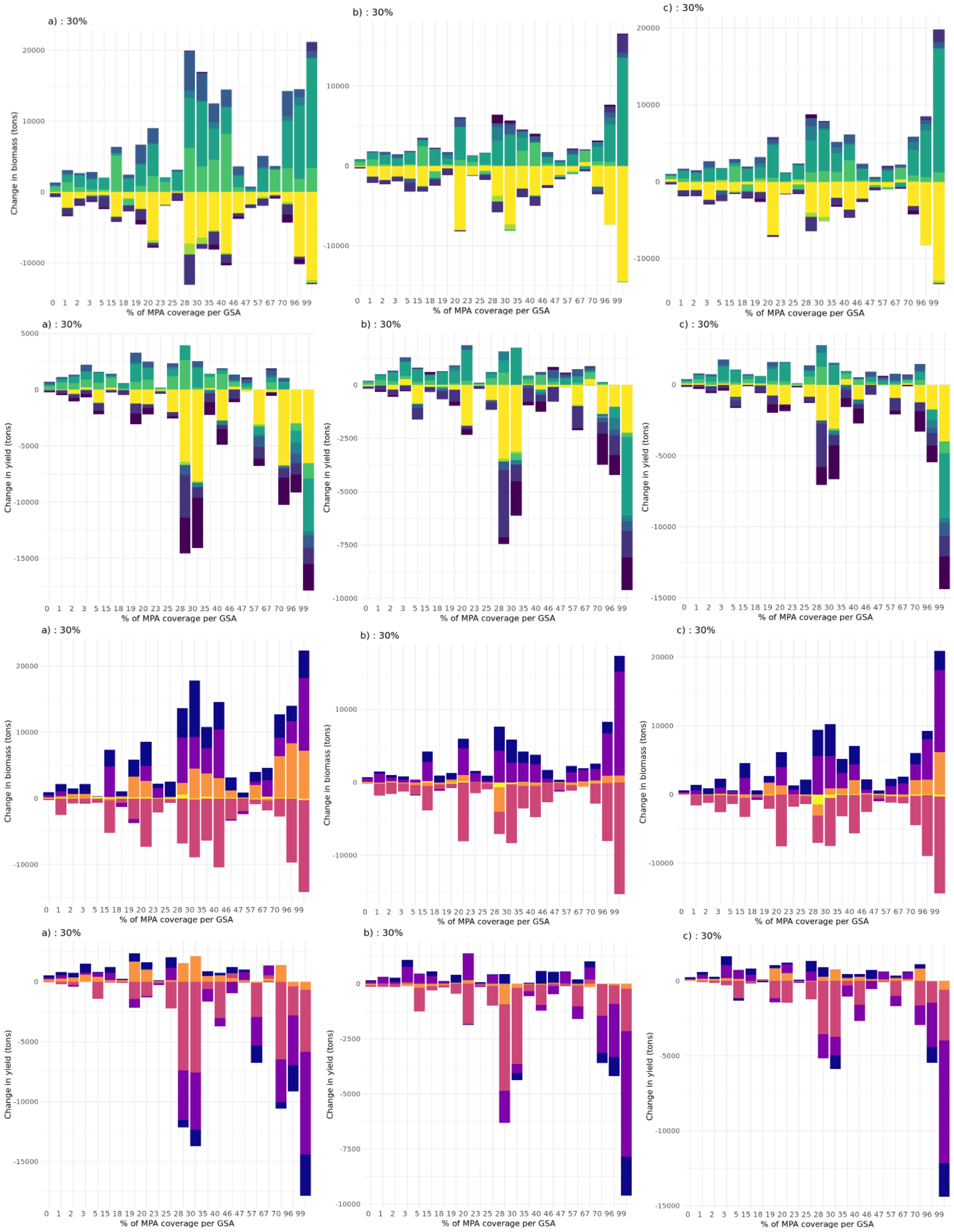
Conversely, the fishing effort reduction (S4) is the worst scenario for bottom trawlers, whether the reduction is 10% or 30%, with their loss in catch amounting to 50,000 tons, representing a loss of ca. €500 million (Figure 7). The fishable biomass that is not fished by bottom and shrimp trawlers anymore may eventually benefit artisanal fleets.
As expected, bottom trawlers are negatively impacted in all scenarios. No-take (S1) and PPA (S2) scenarios imply the same restrictions towards them and therefore the same catch change. The multi-zone scenario (S3) results in a lower catch change. For artisanal fleets, although there is an increase in catch, it is offset by a lower gain in landed value. Indeed, as observed previously (Figure 5), the catch change for all species groups is lower under this scenario. It is however interesting to note that even in a scenario banning areas for all fleets, bottom trawlers are impacted at the same level, indicating that they do not seem to take advantage of the spill-over effect or that they have no remaining areas to be relocated to.

As for purse seiners and pelagic trawlers, their catches drop substantially, due to the decline of small pelagic species biomass (Figure 5), exceeding 25,000 tons in a no-take scenario (S1) with a 30% MPA coverage (Figure 7). Indeed, this loss is mostly driven by the European anchovy *Engraulis encrasicolus* and the European pilchard *Sardina pilchardus,* representing 81% and 18% of the catch loss, respectively. The purse seiners and pelagic trawlers' economic loss is however far smaller than that of bottom trawlers, €30 million against €320 million. In fact, small pelagics are significantly less valuable than the targets of bottom trawlers, ca. €2/kg for the common anchovy versus ca. €6/kg for the European hake.

Longliners and tuna purse seiners are not much affected by management scenarios. Indeed, they target highly mobile species like large pelagics, which struggle to benefit from spatial management due to their migratory behavior (Boerder et al., 2019).

5. Analysis by Geographical Sub-Areas

In the MPA distribution scenario taken from the study of Mazor et al. (2014), the MPA coverage is unevenly distributed across the Geographical Sub-Areas of the Mediterranean Sea, which may conceal other interesting trends. Thus, the changes in biomass, catch and landed value were computed according to the proportion of MPA inside the GSA, for the three MPA scenarios and in a 30% MPA coverage scenario (Appendix II).



a) : 30%
b) : 30%
c) : 30%
Change in biomass (tons)
Change in yield (tons)
% of MPA coverage per GSA
0 1 2 3 5 15 18 19 20 23 25 28 30 35 40 46 47 57 67 70 96 99

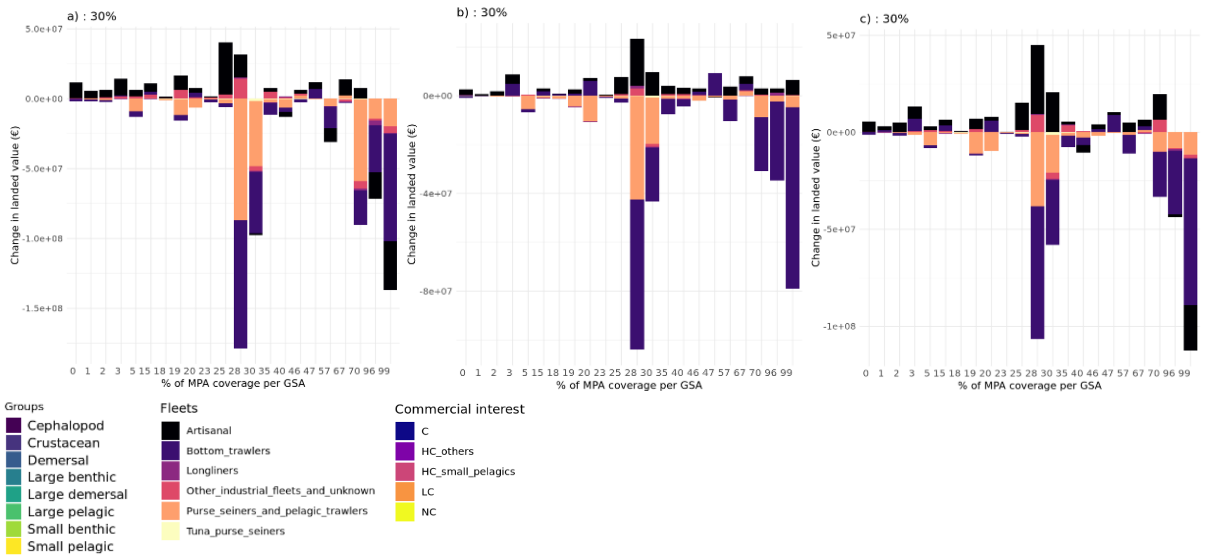


Figure 8: Change in biomass, catch (tons) and landed value (€) by proportion of MPA coverage within GSAs in a 30% MPA coverage for the three scenarios: a) no-take, b) partial, c) multi-zone.

Table 3: GSAs corresponding to proportion of MPAs within GSA.

Percentage of MPA within GSA	GSA number
0	2, 24, 25, 27
1	23, 5
2	11.2
3	9
5	12
15	19
18	1
19	13
20	6
23	11.1
25	4
28	22
30	17
35	10, 18, 21
40	26
46	16
47	8
57	3
67	20
70	14
96	15
99	7

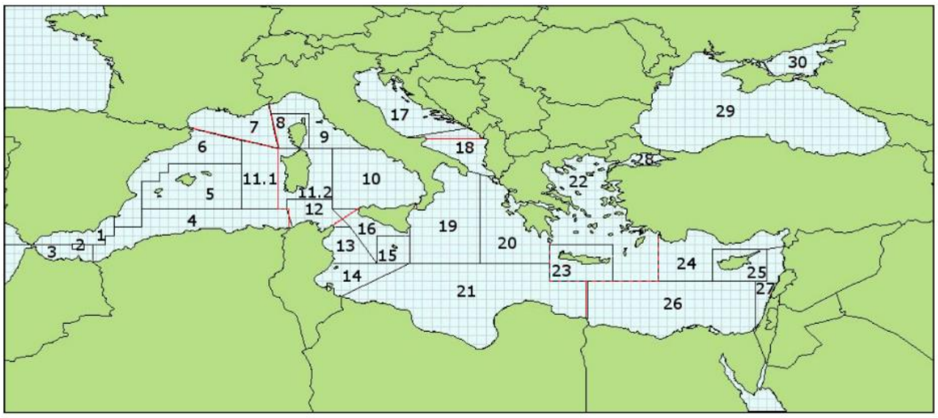


Figure 9: GFCM geographical sub-areas (GSAs) (GFCM, 2009).

Table 4: GSA names and numbers.

01-Northern Alboran Sea	07-Gulf of Lion	13-Gulf of Hammamet	19-Western Ionian Sea	25-Cyprus
02-Alboran Island	08-Corsica	14-Gulf of Gabès	20-Eastern Ionian Sea	26-Southern Levant Sea
03-Southern Alboran Sea	09-Ligurian Sea and Northern Tyrrhenian Sea	15-Malta	21-Southern Ionian Sea	27-Eastern Levant Sea
04-Algeria	10-Southern and Central Tyrrhenian Sea	16-Southern Sicily	22-Aegean Sea	28-Marmara Sea
05-Balearic Islands	11.1-Western Sardinia 11.2-Eastern Sardinia	17-Northern Adriatic Sea	23-Crete	29-Black Sea
06-Northern Spain	12-Northern Tunisia	18-Southern Adriatic Sea	24-Northern Levant Sea	30-Azov Sea

The general trends observed previously for biomass and catch change can be found in this analysis by GSA, especially for biomass change. Predators such as large demersal and pelagic species, as well as commercial and highly commercial species benefit from MPAs whereas small pelagics biomass drops, no matter the proportion of MPA coverage by GSA or the scenario (Figure 8). For these groups, the change is the greatest in the most covered areas (99%), approximately 20,000 tons in the no-take (S1) and the multizone scenarios (S4), 3,000 tons in a partial scenario (S2).

Nevertheless, a larger proportion of MPA in a GSA does not necessarily lead to a greater positive change in biomass and negative change in catch. In a no-take scenario (S1), 35% and 40% MPA coverages by GSA generate changes in biomass close to a 96% MPA coverage in GSA 15 (Figure 8), accompanied with a much lower loss in catch by groups and by fleets, €12 million against €70 million. A 96% and 99% MPA coverage by GSA do not trigger gains in catch no matter the group, logically because fleets have nowhere to fish anymore and cannot benefit from the spill-over effect. This underscores the limits of fishing effort redistribution scenarios that are modeled within GSAs and of the MPA distribution scenario taken from the study of Mazor et al. (2014), in which MPAs are wide areas that can cover almost an entire GSA like the MPAs of Malta and the Gulf of Lion (Figure 9; Tables 3-4).

The PPA (S2) and multizone (S3) scenarios lead to lower positive changes in biomass for 35% and 40% coverages by GSA compared to the no-take scenario (S1), sometimes around three times lower (Figure 8). The PPA scenario (S2) is the scenario that generates the smallest positive biomass changes. However, the no-take scenario (S1) can result in a greater loss for fleets, €170 million in GSAs covered with MPAs by 28% compared to the PPA and multizone scenarios leading to losses of €70 million. The higher effectiveness of the no-take scenario in terms of biomass gain but the most impactful on fisheries catches is a pattern that we found in our previous analysis (Figures 5-7).

Within the same scenario, changes in biomass and catch can vary between close proportions of MPA coverage (Figure 8). Therefore, not only do results depend on the scenario, but they also depend on the MPA coverage within the GSA, and thereby the area that is protected. Consequently, overcovering a GSA with MPAs in the Mediterranean is not always the best option, because some areas can trigger better results in biomass concerning certain groups than others regardless of the MPA coverage. This underlines the importance of strategically identifying and choosing the areas to protect.

In previous results, MPAs favored artisanal fleets and disadvantaged bottom trawlers and purse seiners and pelagic trawlers no matter the coverage and the scenario (Figure 7). Here, we can notice that there are some MPA coverages in which artisanal fleets experience a negative catch change, excepted under a multi-zone scenario, whereas bottom trawlers can experience positive catch change, across all scenarios (Figure 8). It seems that artisanal fleets do not benefit from MPAs mostly in overcovered GSAs, like all the others fleets. These variations may be caused by multiple factors such as a different efficiency among the MPAs due to their size, their location, the relocated fishing effort, the spatial distribution of species and fleet within the Mediterranean Sea. Once again, the conveyed message is to strategically identify areas to protect by taking into account ecological as well as social and economic aspects.

Discussion

1. Key results

1.1. Management measures help rebuild commercial fish stocks

As observed above, despite a rather low total biomass change, management measures such as MPAs and fishing effort reduction play a crucial role in the protection of highly commercial and commercial species. The groups benefiting from this protection are mainly large demersal and large pelagics. Those measures therefore favor high trophic level species and large fish, initially heavily targeted by fishing. These results are consistent with previous findings in the literature (Edgar et al., 2014; Guidetti et al., 2014; Rojo et al., 2021).
MPAs serve as local sanctuaries for high trophic level species, but their impacts extend beyond their boundaries. Evidence suggests that the total biomass change increases not only within the MPA but also at the GSA and Mediterranean scales, indicating a spill-over effect (Di Lorenzo et al., 2016). This effect consists in flows of juveniles, sub-adults and adults from within the protected areas to outside the MPAs. This spill-over effect can also benefit fisheries by increasing the fishable biomass, as long as an increase in fishing pressure around the MPAs (fishing-the-line effect) does not offset the resulting ecological benefits. Implementing MPAs could consequently help rebuild vulnerable and depleted Mediterranean fish stocks, and ensure the sustainability of some fisheries.

On the other hand, the resulting higher predation pressure consequently affects small pelagic species, offsetting the overall increase in fish biomass. Trophic cascades are in fact commonly observed after the establishment of MPAs (Albouy et al., 2010). The significant decrease in yield of some small pelagic species, in particular the European anchovy and the European pilchard, are also highly commercial and the targets of purse seiners and pelagics trawlers that therefore experience a significant decrease in yield.

Consequently, fleets are affected differently by the establishment of management measures.

1.2. Artisanal fleets always benefit from management measures

Looking at the catch change for each fleet, one significant result is that artisanal fleets always seem to benefit from management measures, regardless of their intensity. Indeed, Abello et al. (in prep) found that implementing MPAs would negatively affect total catch change. In this study, we show that this is particularly the case for purse seiners and pelagic trawlers, whose catches are projected to decline due to a decrease in small pelagics biomass because of trophic cascades following the implementation of MPAs, as mentioned previously. However, looking at the value of those catches, the loss is eventually lower than expected because small pelagics have low price value. The most affected fleet by the different management measures tested are bottom trawlers, which will suffer from an important loss in both catch and value. As they have the highest impact on the environment, all tested measures were targeted towards them. The reduction in trawler catches seems to be to the advantage of small-scale artisanal vessels.

Artisanal fleets indeed benefit from the increase in biomass of large fish and highly commercial species and from MPA spill-over (Di Lorenzo et al., 2016), resulting in a rise in catches, even when restricting their fishing area through the implementation of no-take areas (management scenarios S1 and S3). This underscores the importance of studying the impacts at the fleet scale, especially in the Mediterranean Sea where there is a wide diversity of fleets and gears that target multiple species. As small-scale artisanal fisheries represent 82% of the Mediterranean fleet and represent the biggest source of employment (FAO, 2022), implementing MPAs may not jeopardize the sustainability of the entire Mediterranean fishing sector but rather support an important part of its activities.

These results nonetheless raise a question about the choices that must be made in the future about the prioritization of certain fleets and gears activities, and the targets of restriction measures. The most impactful fleets like bottom trawlers are set to be reduced as it is already the case in the Gulf of Lion with the West-Med Plan (European and Parliament Council, 2019). This supposes a shift in activities, that may be a transition from impactful industrial activities using active gears towards more artisanal fishing using passive gears, as supported by many scientists (Gascuel, 2023). Transition implies economic support for affected fishers and for the sector in order to facilitate this shift. Such plans already exist in other areas, like « le Plan de sortie de flotte » aiming to help fishers affected by the Brexit to sell their activities and transition (Europe en France, 2023). To be effective, such plans must take into account all the economic impacts on the sector to ensure a successful adaptation and sustainability. Nevertheless, implementing such measures may be crucial for the future of fishing in the Mediterranean Sea, in order to rebuild its 58% overexploited fish stocks.

1.3. The location of MPAs may be more important than the extent of their coverage

The results observed on Figure 8 reveal the same trends in biomass and in catch than that of the non-spatialized results. The no-take scenario is again the one that allows the greatest increase in biomass. However, this spatialized analysis enables us to see that the outcomes of the establishment of MPAs do not seem to depend much on the proportion of those MPAs within a GSA but on the location and the region in which they are implemented. Indeed, lower coverages can generate equivalent or better results in biomass or catch change than wider coverages in MPAs. For instance, in a PPA scenario, a 35% MPA coverage in GSA 18 (Southern Adriatic Sea) generates greater positive biomass change by groups as well as lower negative catch change than a 70% MPA coverage in GSA 14 (Gulf of Gabès). Furthermore, GSAs with close proportions of MPAs produce very different results. This spatialization of the effectiveness of MPAs has already been reported by Abdou et al., (2016) and in particular by Abello et al. (in prep), who observed that scenarios emerging from a selection of priority areas to protect lead to better results than scenarios that do not take into account the specifity of each region like random or uniformly distributed by EEZ MPA scenarios.

Moreover, not only do the most protected GSAs in fact not experience better results than less protected areas, but they also often result in negative catch change for all fished groups, and therefore a higher impact on fleets. Even fleets favored by the different management scenarios , such as artisanal fleets (Figure 7), will be negatively impacted in areas where MPA coverage is very high , like in GSA 15 (Malta) or in GSA 3 (Southern Alboran Sea), where only 4% or 43% of the area remains unprotected in a 30% MPA coverage scenario, respectively. The significant catch loss of the 70% MPA coverage in GSA 14 (Gulf of Gabès), 96% MPA coverage in GSA 15 (Malta) and of the 99% MPA coverage in GSA 7 (Gulf of Lion) can easily be attributed to the fact that, after the establishment of the MPAs, vessels have a very limited area to relocate to. This leads to a great increase in fishing effort and competition for catch in those areas, which also prevents fisheries from benefiting from the spill-over effect, thereby explaining the substantial decline in catch. Therefore, protecting the most and widest areas with MPAs cannot be the solution as all fleets would be negatively affected. Consequently, the strategy resides in a wise selection of areas to protect, taking into account their spatialized effectiveness, in order to find the best trade-off between ecosytem protection and sustainability of the fisheries.

1.4. Comparison between management scenarios

Some studies criticize the effectiveness of MPAs, arguing that non-spatial management measures, such as reduction in fishing effort and increasing selectivity, are far more useful to meet conservation goals (Hilborn, 2018). In this study, we show that MPAs can provide benefits that non-spatial management measures may not offer. For instance, the no-take scenario triggers the highest biomass increase, whether considering total biomass, functional groups or commercial interest species, compared to the fishing effort reduction, as confirmed in some studies (Costello & Ballantine, 2015; Edgar et al., 2014). Furthermore, when the MPA network is expanded to 30%, the no-take scenario is the only scenario offering a rise in biomass of low-commercial and non-commercial species, enhancing its effectiveness.

The fishing effort reduction scenario's results were close to the PPA scenario's ones. Those scenarios are in fact two different ways of managing the same fleet, bottom trawlers. Partially protected areas, representing the biggest part of global MPAs, are however widely criticized in the literature for not guaranteeing benefits (Turnbull et al., 2021), leading to « paper parks » (Relano & Pauly, 2023). Conversely, reducing fishing effort was shown to increase total biomass and catch of high trophic and commercial species (Fouzai et al., 2012; Moullec et al., 2023). This scenario may as well be easier to implement than a no-take scenario and result inlower social costs (Gill et al., 2024), such as less important catch losses for fleets, and an overall better fisheries-conservation tradeoff. Our results suggest that combining spatial and non-spatial management strategies may be a suitable option in the Mediterranean Sea, worth testing in future work.

This explains the simulation of a multi-zone scenario, which initially appeared to be the best compromise, as its application had been shown to enhance fish biomass (Corrales et al., 2020;

Gill et al., 2024; Rojo et al., 2021). However, this scenario was ultimately not as effective as expected. One explanation could reside in the fact that the multi-zone scenario did not perform well in a 10% MPA coverage scenario because the no-take area only represented 3% of the Mediterranean Sea. Moreover, in both fishing redistribution scenarios tested and, in particular, in the Proportional by GSA scenario (Figure 3), fleets fishing inside the no-take area will be relocated to adjacent areas, i.e. in the partially protected area. Due to increased fishing pressure inside the PPA, the multi-zone MPA might most likely resemble a three times smaller no-take MPA. Consequently, a scenario where the partially protected area of the multi-zone MPA is restricted to all industrial fleets may be more efficient and could be worthtesting.

2. Limits and perspectives

2.1. A challenging modeling of fleets, their costs and benefits and the redistribution of their effort

Modeling fleets of the Mediterranean Sea was a complex challenge due to their high diversity and the limited data availability. As mentioned before, the Mediterranean Sea is characterized by a wide range of different gears and fleets targeting multiple species. The Mediterranean Sea being bordered by twenty-one countries, fleets present different characteristics from one country to another. This adds another layer of difficulty to find and collect reliable data in order to accurately model those fleets at a basin-scale.
The data used in the parameterization of these fleets was collected from the Sea Around Us project. Although this source may not be completely ideal because based on estimations, it provided data that was scarce or difficult to collect. This data-poor context obliged a simplification of fleet diversity in the model, potentially overlooking a part of it and its impact on the ecosystem.

The collection of catch data in tons and in value to estimate species price was also challenging. To limit the bias and create the most complete database, both data sources were used, the Sea Around Us project and the data from the Scientific, Technical and Economic Committee for Fisheries (STECF) of the European Union. Based on declarations of the European Mediterranean countries only, the latter provided the less complete database but likely the most reliable data for the main European countries exploiting the Mediterranean Sea. Conversely, the Sea Around Us projet presented a range of data including more countries, more species and more areas, but partially based on declarations and estimations, so possibly overestimating the values of catches in tons and value. The data filtering process intended to limit the bias of both datasources though their inherent limitations challenge an accurate modeling of the economic gain or loss of the fleets.

Furthermore, these economic changes only take into account the value of catches, which may also bias the impact of fisheries management measures. Indeed to assess these impacts more accurately, costs of maintenance and production could also be accounted for (Erauskin-Extramiana et al., 2024). For example, fleets being redistributed after the implementation of MPA networks might require more fuel or maintenance to keep their activity going, underlining the limits of the current fishing effort redistribution scenarios.

The fishing effort redistribution scenarios were selected based on the literature (Abello et al., in prep; Hoos et al., 2019), but they also present limitations. First, the Uniform by GSA scenario (Figure 3) cannot reflect in itself the redistribution of the fishing effort after the establishment of an MPA as each fleet has fishing zones, its targets and strategies and its limitations regarding

the distance they can travel from their home port. The Proportional by GSA scenario attempts to simulate this preservation of fishing zones and strategies, but is also biased, as in reality some fleets may relocate and find new fishing areas. Averaging both scenarios comes from the assumption that the redistribution of fishing effort after the establishment of an MPA is neither totally one nor the other but may be somewhere in between.
Second, the averaged fishing effort redistribution scenario was applied to all the fleets without taking into account the inherent different fishing strategies that characterize them, which surely biases the results. The bias may mostly come from the modeling of the artisanal fleet fishing effort. When redistributed, artisanal fleets are more unlikely to fish on the other side of the GSA or in areas far from the coast. Furthermore, one common effect of the establishment of MPAs that was overlooked is the fishing-the-line effect, which describes the redistribution of fishing effort in a close area surrounding the MPA in order to benefit from spill-over effect and therefore increase catch rates (Cabral et al., 2017; Kellner et al., 2007; Murawski et al., 2005). The major constraint was technical as it resides in the resolution of the model that limits an accurate distribution of the fishing effort, each cell measuring 20 x 20 km².
In Abello et al. (in prep), fishing effort redistribution strategies produced different results of biomass and catch change indicating their importance and the sensitivity of the results to the redistribution strategies. Therefore, in further studies, an improvement of the modeling by specifying strategies by fleet should be undertaken.
Finally, due to the closure of areas and the redistribution of fleets, some vessels may be relocated too far from their home port. When taking into account the energy and maintenance costs needed to realize such distance, these vessels might experience a negative profit and become unsustainable. As a result, some fishers might either stop their activity or switch to alternatives, such as another gear, other target species or another metier. This would either lead to a reduction or a shift in redistribution of fishing effort.
Consequently, a future perspective could aim, with fleet-specific fishing effort redistribution strategies, at defining a threshold in total fishing cost, beyond which fishers would either stop their activity or switch to another target species or gear.

During this study, two important factors were not accounted for, thereby biasing the economic impact of those management measures on fisheries. First, climate change is projected to deeply impact marine ecosystems and fisheries, especially in the Mediterranean Sea (Moullec, Barrier, et al., 2019; Pita et al., 2021) due to the combination of ocean warming, acidification and oxygen depletion (Cashion et al., 2020), therefore leading to a decrease in catch of fisheries. Climate change may also mitigate the benefits of MPAs (Bruno et al., 2018; Cheung et al., 2024), hence preventing fleets benefiting from their spill-over effect to increase their catches and even lose catches due to climate change.
Secondly, the climate-induced spread of invasive species (Azzurro et al., 2019, 2019; Coll et al., 2010) was partially taken into account in this study, with the modeling of four invasive species. However, this aspect should be further investigated. Their spread could alter trophic relationships and affect the distribution of endemic species, and could impact fisheries by either replacing their target species or becoming new targets themselves. New markets could emerge from these new species that would therefore constitute a new source of revenue for the fishers. These shifts would change the assessment of their benefits and costs.

Last but not least, one key limitation in the modeling of fleets in this study is the exclusion of recreational fishing. Indeed, the Mediterranean Sea is highly touristic and recreational fishing is abundant (Cappato, 2011; ICOMIA, 2018), particularly in coastal areas. These practices involve spearfishing, boat-fishing and shore-fishing. Even though recreational fishing pressure is generally lower than commercial fishing pressure, their impact must not be underestimated

(Lewin et al., 2019), especially when combined with high commercial fishing pressure. Recreational fishing can limit the benefits of MPAs as is the case in the Bonifacio Straits Natural Reserve (BSNR) Corsica, where combined recreational and commercial fishing pressures have been shown to mitigate the effectiveness of the MPA (Albouy et al., 2010).
Ideally, both fishing activities should be taken into account to better estimate fishing effort occurring in the Mediterranean Sea and future research could focus on this aspect. However, modeling such fleets is an even bigger challenge than for commercial fisheries due to the lack of data.

2.2. Management measure scenarios

The spatial management measure scenarios conceived in this study were based on a distribution of MPAs selected by Mazor et al. (2014). Using an optimization algorithm, the areas selected for protection are assumed to offer the best trade-off between increasing biomass and reducing catches. This scenario was tested in Abello et al. (in prep) and compared to a wide range of other MPA scenarios. As it offered the best trade-off compared to other scenarios at the scale of the whole Mediterranean Sea, and in order to allow comparison between fleet-specific fishing management scenarios, it was chosen to be tested here. We preferred focusing on comparing different management measures within a single MPA distribution rather than expanding the number of MPA distribution scenarios.
Nevertheless, the MPA scenario tested (Mazor et al., 2014) can easily be criticized as it consists in wide areas being completely banned to fishing, sometimes covering up to an entire coastline such as the Gulf of Lion. This scenario may be the best trade-off at the Mediterranean scale but cannot realistically be implemented locally. In order to ensure better equity, the EEZ-scale conservation scenario in Abello et al. (in prep) could also be tested so that MPA networks would be evenly distributed accross the Mediterranean Sea. Those areas are however selected randomly. Therefore, an ideal scenario could combine this optimization of a trade-off between protecting the ecosystem and ensuring fisheries sustainability and selecting priority areas with a more even distribution or a size limit, so that MPAs cannot cover the entire coastline of a country, ensuring its potential applicability. The establishment of MPAs must integrate social and economic aspects. Horta E Costa et al. (2022) imagined a participatory process with stakeholders to elaborate different scenarios of MPAs and select the one that could be applicable for them. This type of process may be a good example of how MPAs distribution scenarios should be defined.

Sève et al. (2023) showed that a network of MPAs was as efficient as a single large MPA, but offered greater fisheries incomes in areas in between MPAs when MPAs were connected through larval dispersal. Ideally, a scenario of MPAs could try to take into account this criteria at the Mediterranean scale by making sure that larval connectivity is possible between the MPAs making up the network (Andrello et al., 2013; Di Franco et al., 2015). However, the current version of the model does not enable to do this yet, but this constitutes an interesting point to explore.

Moreover, in order to mitigate the effects of climate change, Cashion et al. (2020) designed a dynamic MPA network that adapts to the shift of species distribution due to the ocean rise in temperature, the acidification and oxygen depletion from climate change. In a study taking into account climate change, future research could try to focus on this aspect at the Mediterranean Sea scale.

In addition to spatial management measures, reducing gear selectivity is a strategy that could be explored. The Mediterranean Sea is in fact characterized by a low fishing selectivity leading to high juvenile mortality, especially in bottom trawling (Colloca et al., 2013). Some studies show that reducing fishing selectivity would indeed increase the total biomass and catch change of high trophic level species thereby mitigating the effects of climate change (Moullec et al., 2023). Therefore, it would be interesting to test this non-spatial management measure scenario, which we had considered during the elaboration of scenarios. However, the current fleet parameterization of the model does not allow changes in fishing selectivity and would probably lead to unexplained species collapses. Overcoming this limitation would be necessary in order to test this scenario.

It would also be interesting to explore a combination of spatial and non-spatial scenarios. Due to time constraint, we did not test any scenario combining a reduction in fishing effort combined to an MPA implementation, but future research could focus on this aspect.

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Appendices

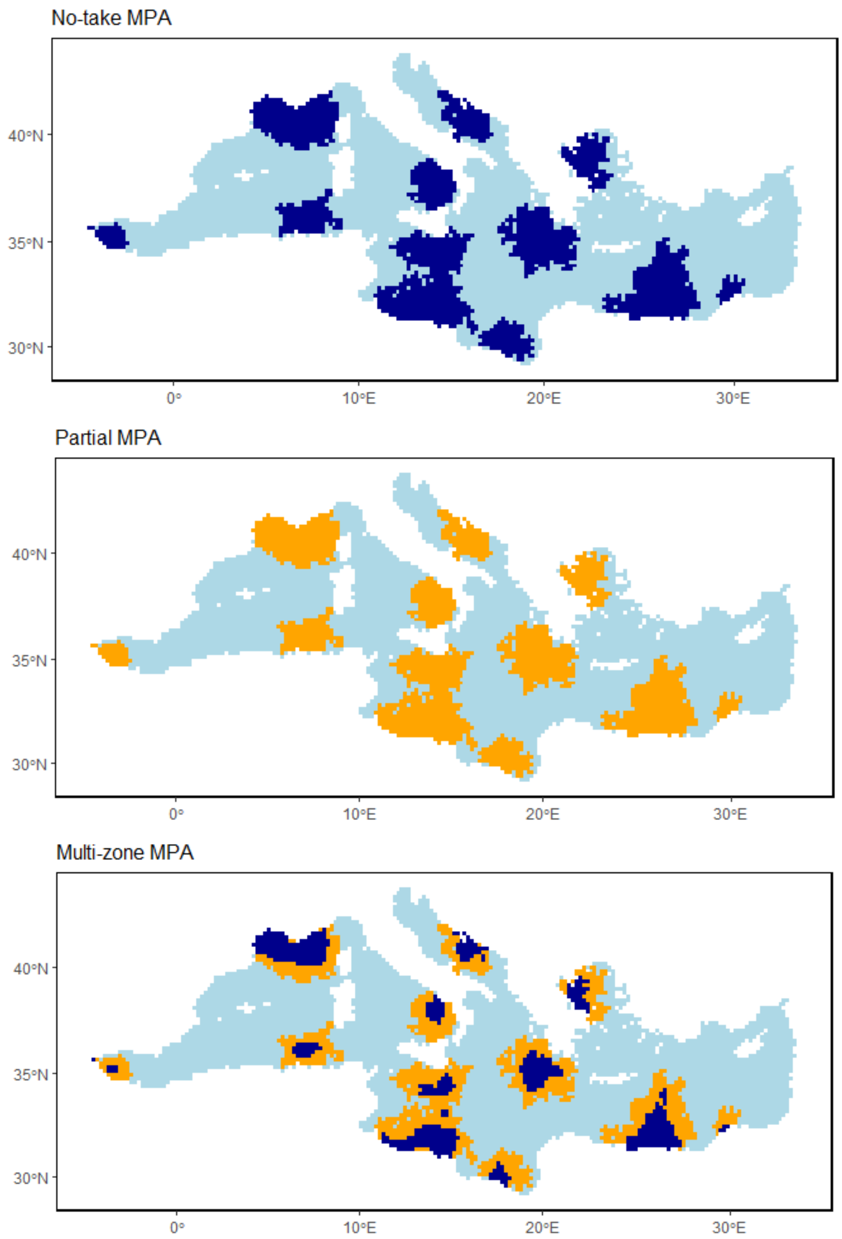
Appendix I: Classification of species by groups and commercial interest.

Species id	Species name	Group	Commercial interest
4	Argyrosomusregius	Large demersal	C
5	Aristaeomorphafoliacea	Crustacean	HC_others
6	Aristeusantennatus	Crustacean	HC_others
7	Atherinaboyeri	Small pelagic	C
8	Auxisrocheirochei	Large pelagic	C
9	Belonebelone	Large pelagic	LC
10	Boopsboops	Demersal	C
11	Caranxcrysos	Large pelagic	NC
12	Chelidonichthyslucerna	Demersal	C
13	Corisjulis	Small benthic	LC
14	Coryphaenahippurus	Large pelagic	HC_others
15	Crangoncrangon	Crustacean	C
16	Crystallogobiuslinearis	Small benthic	NC
17	Dentexdentex	Large demersal	C
18	Dentexgibbosus	Large demersal	LC
19	Dentexmaroccanus	Demersal	NC
20	Dicentrarchuslabrax	Large demersal	HC_others
21	Diplodusannularis	Demersal	C
22	Diploduscervinus	Demersal	C
23	Diploduspuntazzo	Demersal	C
24	Diplodussargussargus	Demersal	C
25	Diplodusvulgaris	Demersal	C
26	Eledonecirrhosa	Cephalopod	C
27	Engraulisencrasicolus	Small pelagic	HC_small_pelagics
28	Epinephelusaeneus	Large demersal	LC
29	Epinephelusmarginatus	Large demersal	C
30	Etrumeusteres	Small pelagic	LC
31	Eutriglagurnardus	Demersal	LC
32	Galeusmelastomus	Large demersal	LC
33	Gobiusniger	Small benthic	LC
34	Halobatrachusdidactylus	Large benthic	LC
35	Illexcoindetii	Cephalopod	C
36	Lepidorhombuswhiffiagonis	Small benthic	LC
37	Lizaaurata	Large pelagic	LC
38	Lizaramada	Large pelagic	NC
39	Lizasaliens	Large pelagic	NC
40	Loligovulgaris	Cephalopod	HC_others
41	Lophiusbudegassa	Large benthic	HC_others
42	Lophiuspiscatorius	Large benthic	HC_others
43	Merlangiusmerlangus	Large demersal	C
44	Merlucciusmerluccius	Large demersal	HC_others

45	Micromesistiuspoutassou	Large demersal	C
46	Mugilcephalus	Large pelagic	C
47	Mullusbarbatusbarbatus	Large benthic	HC_others
48	Mullussurmuletus	Large benthic	HC_others
49	Mustelusmustelus	Large demersal	LC
50	Nephropsnorvegicus	Crustacean	HC_others
51	Octopusvulgaris	Cephalopod	HC_others
52	Pagellusacarne	Demersal	C
53	Pagelluserythrinus	Demersal	HC_others
54	Pagruspagrus	Large demersal	C
55	Palaemonserratus	Crustacean	C
56	Palinuruselephas	Crustacean	C
57	Parapenaeuslongirostris	Crustacean	HC_others
58	Penaeuskerathurus	Crustacean	HC_others
59	Phycisphycis	Demersal	LC
60	Platichthysflesusflesus	Large benthic	LC
61	Pleuronectesplatessa	Large benthic	NC
62	Pomatomussaltatrix	Large pelagic	C
63	Pomatoschistusmarmoratus	Small benthic	NC
64	Pomatoschistusminutus	Small benthic	NC
65	Rhinobatosrhinobatos	Large benthic	LC
66	Sardasarda	Large pelagic	HC_others
67	Sardinapilchardus	Small pelagic	HC_small_pelagics
68	Sardinellaaurita	Small pelagic	C
69	Sauridaundosquamis	Demersal	C
70	Sciaenaumbra	Large demersal	C
71	Scomberjaponicus	Small pelagic	C
72	Scomberscombrus	Small pelagic	C
73	Scophthalmusmaximus	Large benthic	C
74	Scorpaenanotata	Small benthic	NC
75	Scyliorhinuscanicula	Large demersal	C
76	Sepiaofficinalis	Cephalopod	HC_others
77	Serioladumerili	Large pelagic	HC_others
78	Serranusatricauda	Demersal	NC
79	Soleasolea	Large benthic	HC_others
80	Sparusaurata	Demersal	HC_others
81	Sphyraenasphyraena	Large pelagic	LC
82	Sphyraenaviridensis	Large pelagic	NC
83	Spicaramaena	Demersal	LC
84	Spicarasmaris	Small pelagic	C
85	Spondyliosomacantharus	Demersal	LC
86	Sprattussprattus	Small pelagic	LC
87	Squillamantis	Crustacean	HC_others
88	Stephanolepisdiaspros	Demersal	NC
89	Thunnusalalunga	Large pelagic	HC_others
90	Thunnusthynnus	Large pelagic	HC_others

91	Trachurusmediterraneus	Small pelagic	HC_small_pelagics
92	Trachuruspicturatus	Small pelagic	C
93	Trachurustrachurus	Small pelagic	C
94	Trachyrincusscabrus	Demersal	LC
95	Triglalyra	Small benthic	LC
96	Trisopterusluscus	Demersal	LC
97	Trisopterusminutus	Demersal	C
98	Upeneusmoluccensis	Demersal	HC_others
99	Xiphiasgladius	Large pelagic	HC_others
100	Zosterisessorophiocephalus	Small benthic	NC
101	Zosteuphausiids	Small pelagic	NC

Appendix II: Scenarios of networks of Marine Protected Areas for a 30% coverage, tested in this study based on (Mazor et al., 2014). Blue: ban for all fleets. Orange: ban for highly impactful gears only (here, bottom and shrimp trawls).



Abstract

The Mediterranean Sea, encompassing 4-18% of global marine biodiversity, is considered to be a hotspot of biodiversity. Surrounded by twenty-one countries, it is also characterized by a wide diversity of fleets and fishing gears, with a great majority of small-scale artisanal fisheries. However, due to poor management of fishing pressure, more than half of its stocks are overexploited. In order to mitigate those effects, targets of spatial protection or fishing effort reduction have been set. In alignement with those decisions, we tested scenarios of expansion of Marine Protected Areas (MPAs) as well as fishing effort reduction. Using the integrated spatial trophic model OSMOSE-MED, we assessed the impact of these measures on fish populations and fisheries, with a particular focus on the latter, to determine the feasibility of these scenarios and identify those that offer the best comprise between biodiversity conservation and sustainability of fisheries. Our findings show that MPAs protect highly commercial and commercial species, besides small pelagic species, and therefore help rebuild stocks. Furthermore, even though management measures may affect the most impactful fisheries, artisanal fleets benefit from them even when restricted, regardless the intensity of measures. Finally, the efficiency of MPAs depends more on their location than on their proportion of coverage area within the Geographical Sub-Areas.

La mer Méditerranée, abritant 4 à 18% de la biodiversité marine mondiale, est considérée comme un point chaud de biodiversité. Entourée par 21 pays, elle est également caractérisée par une grande diversité de flottilles et d'engins de pêche, avec une majorité de pêcheries artisanales. Toutefois, due à une mauvaise gestion de la pression de pêche, plus de la moitié de ses stocks sont surexploités. Dans le but d'atténuer ces effets, des cibles de gestion spatiale et de réduction de l'effort ont été fixées. En accord avec ces décisions, nous avons testé des scénarios d'expansion du réseau d'Aires Marines Protégées (AMP) ainsi que de diminution de l'effort de pêche. A l'aide du modèle trophique intégré et spatialisé OSMOSE-MED, nous avons estimé l'impact de ces mesures sur les populations de poisson ainsi que les flottilles de pêche, avec un accent sur ces dernières, afin de déterminer la faisabilité de ces scénarios et d'identifier ceux qui offrent le meilleur compromis entre conservation de la biodiversité et durabilité économique des flottilles. Nos résultats montrent que les AMP protègent les espèces commerciales et hautement commerciales, hormis les petits pélagiques, permettant ainsi une reconstitution des stocks. De plus, bien que les mesures de gestion nuisent aux pêcheries les plus impactantes, les pêcheries artisanales en bénéficient même quand elles sont restreintes, peu importe l'intensité des mesures. Enfin, l'efficacité des AMP dépend davantage de leur localisation que de la proportion de leur couverture au sein des Sous-Aires Géographiques.