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Exploring spatial-based management scenarios to protect the seafloor in different areas of the Mediterranean Sea

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Abstract

In recent years, European policies aimed to regulate bottom trawling activities, given the significant environmental damage they cause. Trawling represents a considerable source of income for the economies of many Mediterranean countries. Therefore, it is essential that management measures, including spatial closures, consider the potential long-term consequences of their implementation. This study investigated the impact of different spatial management scenarios on reducing the environmental footprint of bottom otter trawling in four distinct sectors (Western, Southern, Adriatic, and Ionian) of the Mediterranean Sea. Using vessel monitoring systems and logbook data, the study identified core fishing grounds and modelled the effects of various spatial restrictions, including depth-based fishing bans and fishery-restricted areas (FRAs). The results indicate that in all the sectors, the adoption of FRAs does not lead to significant variations in the economic performance of fleets, and the application of the ban over 800 m would allow the protection of a significant portion of the deep-sea bottom with relatively little economic impact. On the contrary, other spatial-based measures lead to different, sector-specific effects. In fact, restricting shallow coastal areas (<6 nm) significantly affects the profitability by reallocating effort to other fishing grounds, with noticeable differences between fleets operating in the same sector (i.e. the Adriatic Sea); meanwhile, bans over 600 or 700 m would determine very different economic effects in the four sectors. Overall, these results suggest that a sole fishery management measure approach is inadequate. Tailored region-specific measures are instead essential to balance ecological sustainability and economic outcomes across different Mediterranean regions.

Keywords: fishery sustainability; spatial-based management; bottom otter trawling; ecological modelling; demersal resources; marine strategy framework directive

Introduction

Bottom trawling is a widespread and historically significant fishing method, particularly in the Mediterranean Sea, where it contributes to the regional economy and supports coastal communities by providing food resources. However, trawling has well-documented negative impacts on marine seafloor, biodiversity, and fish stocks, leading to both environmental and socio-economic consequences (Jennings and Kaiser 1998, Hiddink et al. 2006, Pusceddu et al. 2014). To overcome this problem, European policies like the Fisheries and Oceans Pact and the EU Action Plan aim to phase out trawling in marine protected areas (MPAs) by 2030 and reduce its impact on vulnerable species and ecosystems. To achieve these goals, ecosystem-based management approaches are considered essential (Pikitch et al. 2004). In general, the achievement of sustainability targets is based on a combination of different management measures, mostly focusing on catch and fishing effort control, joined with technical measures to regulate the exploitation pattern based on selectivity and spatial and/or temporal closures of fishing activity (Cochrane and Garcia 2009). All these measures must be harmonized within a fisheries management plan in order to contribute to a more sustainable harvest with less impact on ecosystems. However, harvest management measures such as spatial closures can lead to a displacement of fishing efforts (Vaughan 2017). Such closures can affect fishing behaviour by reallocating fishing efforts to less desirable areas and/or encouraging fishermen to aggregate near the boundaries of closed areas, reducing the measure's effectiveness (Vaughan 2017).

A crucial aspect of evaluating commercial fishing is its economic productivity. Understanding and maintaining fishing production is essential to ensure the long-term sustainability of fisheries in the Mediterranean Sea (Liquete et al. 2016). Poor knowledge about fishery distribution and activity can lead to randomly placed closures that ultimately result in a reduction of economic profits (Rassweiler et al. 2012). These responses can affect the entire fishing system, altering catch rates and revenues and promoting conflicts due to overcrowding (Charles and Wilson 2009, Mascia and Claus 2009, Valcic 2009).

In this way, fisheries spatial assessment becomes essential in identifying effective management measures for the sustainable exploitation of marine demersal resources. Nowadays, different platforms forecast the potential effects of spatial-based scenarios using a combination of the vessel monitoring system (VMS), automatic identification system (AIS), and logbook data. In the Mediterranean Sea, different platforms often support the modelling of multispecies fisheries such as bottom trawling, and include (among others) ISIS_FISH, SMART, and DISPLACE (Mahévas and Pelletier 2004, Pelletier et al. 2009, Bastardie et al. 2014, Russo et al. 2014a, Lehuta et al. 2016, D'Andrea et al. 2020), tailored for compatibility with data collected under the EU Data Collection Framework.

Regardless of the model used, the rationale applied can be effectively exemplified by the work done in the context of the International Council for the Exploration of the Sea (ICES) to support the European Commission (ICES 2024a). Starting from the observation that not all fishing areas are equal in terms of production and exploitation, the goal of studying the spatial structure of fishing becomes the identification of 'core grounds' and peripheral areas (*sensu* ICES). ICES reported that, during the period 2017–2022, 90% of landings value for mobile bottom contacting gears (MBCG) came from <50% of the fished area when the percentages are evaluated at the scale of 0.05° latitude × 0.05° longitude c-squares. This outcome could be used to close large areas to fishing with limited economic losses for the fleets. In this perspective, ICES conducted trade-off analyses to estimate the potential costs to MBCG fisheries in terms of reductions in fishing intensity, landings weight, and landings values to achieve a defined percentage of the area (ranging from 10% to 90%, in increments of 10%) of each EU Marine Strategy Framework Directive (MSFD) Broad Habitat Type (BHT) that is left unfished. This exercize indicated that maintaining a persistently unexploited state in 70% of the extent of all MSFD BHTs within the overall area is associated with an estimated reduction of 20% (for the Greater North Sea and the Celtic Seas areas) and 7% (Baltic Sea) of the annual mean MBCG landings value. However, this promising approach applied by ICES is still in progress since several limitations characterize it. These include the omission of data due to lack of VMS coverage for fishing vessels with Length-overall (LOA) < 12 m, the use of landings value rather than profits as a measure of economic impact, and the lack of modelling of effort displacement and related effects on landing, landing values (LV), and profits. The approach is anchored primarily in the economic and social sustainability pillars without considering environmental sustainability (e.g. looking at valuable biodiversity areas).

In light of these considerations, and within the framework of the EU research project ABIOMMED (https://www.abiommed.eu/), this study aims to assess the effects of different spatial-based measures for managing bottom trawling and reducing their negative impact on the seabed while maintaining the productivity of fisheries. Our work took advantage of two complementary modelling approaches. The first one identified the best trade-off between seabed protection and the economic sustainability of fishing activities. The second one evaluated the displacement of fishing efforts as a response to the application of different management measures. Moreover, it assessed the consequent redistribution in the composition of catches and the resulting change in the economic scenario. The work is focused on four case studies in different subregions of the Mediterranean Sea, using AIS, VMS, and Logbook data at the scale of individual vessels (Fig. 1).

This study supports the identification of spatial-based measures, primarily spatial closures, that can be used, in the framework of the MSFD, to implement an ecological approach to fishery management in different sectors of the Mediterranean Sea.

Materials and methods

Study area

The study focused on four case studies, defined as groups of contiguous FAO geographical subareas (GSAs), corresponding to different Mediterranean sectors defined within the MSFD. Namely, the Western sector, including the Sardinian Sea (GSA 11.1 and 11.2), the North Tyrrhenian Sea (GSA09), and the South Tyrrhenian Sea (GSA10); the Southern sector, including the Strait of Sicily (GSA 12–16), the Adriatic sector, including the Adriatic Sea (GSA17 and 18), and the **Ionian sector**, including the Eastern Ionian Sea (GSA19) (Fig. 2). Details about the morphological characteristics of the different sectors are provided in the Supplementary materials. Three of these four case studies were related to Italian fleet activities,

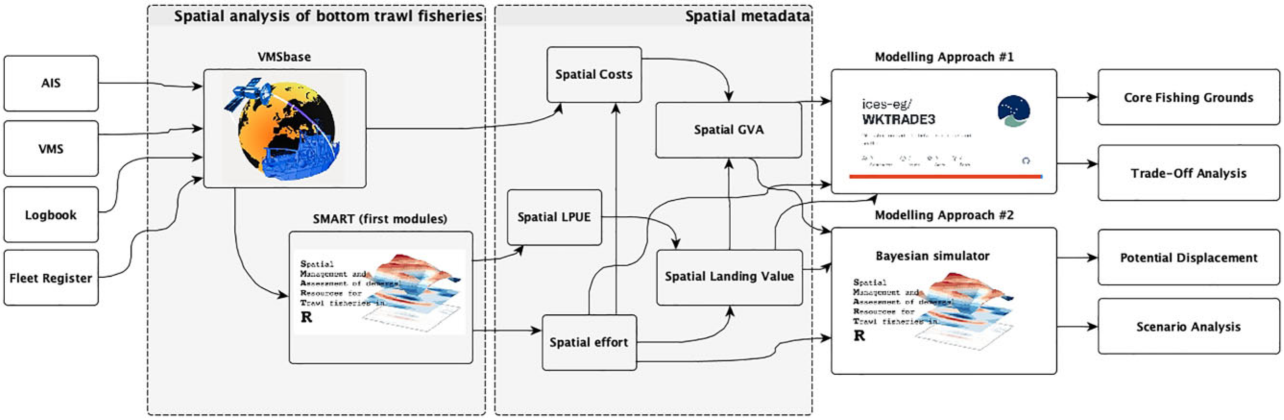

Figure 1. Representation of the workflow applied in this study.

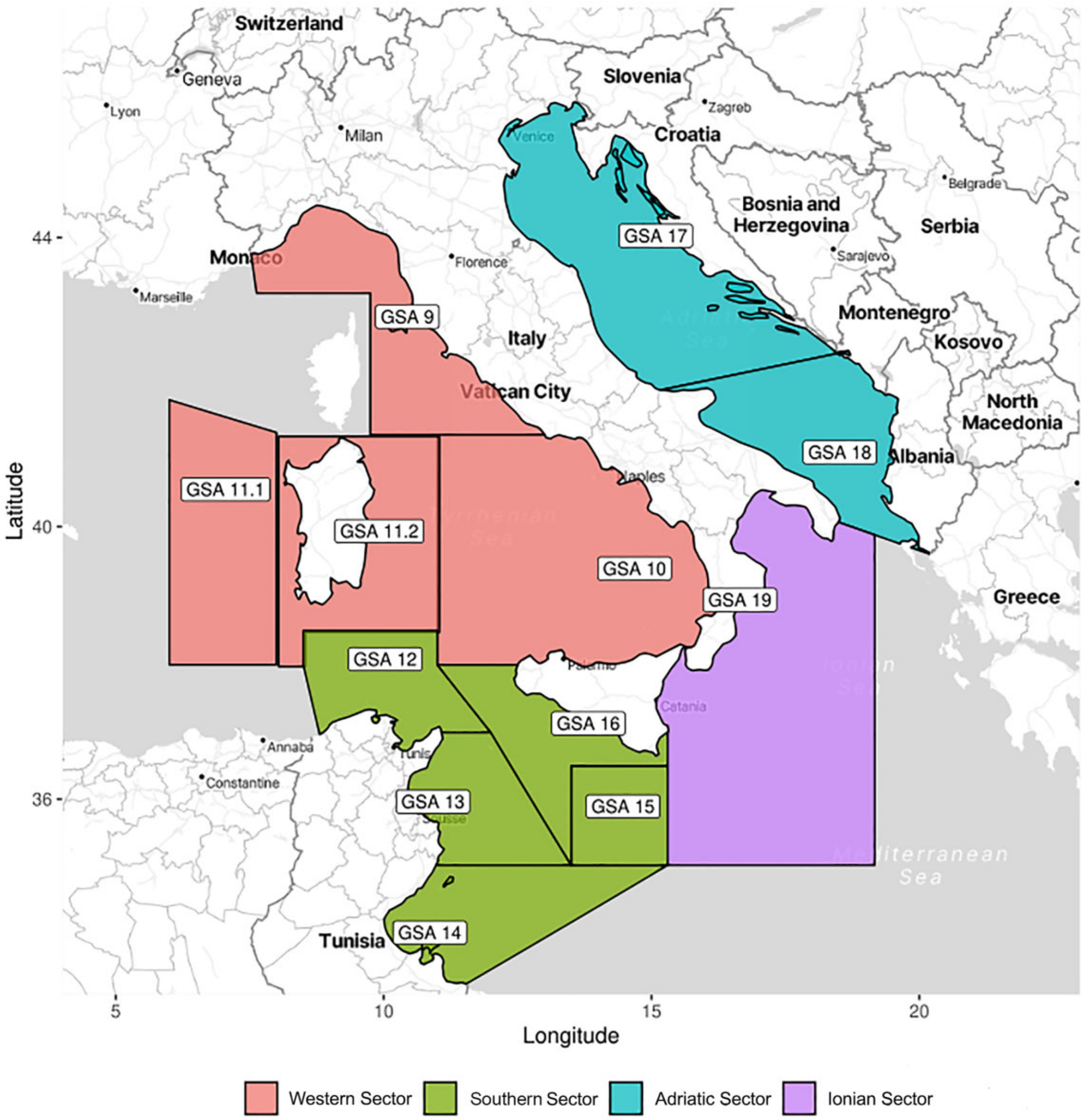

Figure 2. Location of the four sectors in the Mediterranean Sea with respect to the GSAs defined by the General Fisheries Commission for the Mediterranean (https://www.fao.org/gfcm/data/maps/gsas/es/).

while only the Adriatic sector analysed Italian and Croatian fleets.

Integrated analysis of VMS, AIS, and logbook data

VMS and logbook data for the Italian trawlers with overall lengths ≥15 m were provided by the Italian Ministry of Agriculture, Food Sovereignty and Forests. The corresponding Croatian data were available from the FAIRSEA project (https://programming14-20.italy-croatia.eu/web/fairsea). AIS data were provided by Global Fishing Watch (https://globalfishingwatch.org/) and merged/integrated with VMS data of the Italian fleet using the VMSbase R package (Russo et al. 2014b) and the procedures described in Russo et al. (2016), to obtain a reliable reconstruction of fishing activity. The datasets for the years 2017–2021 were considered for all the investigated areas. A summary table of these data is presented in Table S1. All the spatial analyses were conducted after defining, for the Western, Southern, and Ionian sectors a 1 km square grid. A 2 km square grid was used for the Adriatic sector to minimize the computational time required since almost the entirety of this basin is exploitable by trawling due to the high presence of soft-bottom substrates and shallow average depth. Moreover, the Adriatic sector was subdivided into two main areas identified by the Adriatic midline—border Italy/Croatia (Line of delimitation of the continental shelf common to the States of the Italian Republic and the Croatian Republic in the Adriatic Sea) (https://data.europa.eu/data/datasets/midline-delladriatico-confine-italia-croazia1?locale=en).

Data were first processed to quantify fishing effort at a seasonal scale for each area as trawling time (total hours of fishing per vessel/month). Preliminary VMS and logbook data analyses allowed the spatial structure of the bottom otter trawl fisheries in the four case studies to be reconstructed. The following statistics were computed for each case study:

- The total area of the seafloor (in km^2) in the bathymetric range 0–1000 m. This statistic represents the potential domain available for bottom otter trawl fishing.
- Area (with respect to the case study-specific grid) actually exploited by bottom otter trawl fishing (mean over the years considered).
- Ratio between the two previous values.

The estimated effort per cell and the amount of catch were combined at a monthly scale, to assess the landing-per-unit-of-effort (LPUE as kg/h fishing/m of vessel length) of the main 16 demersal species (those accounting for 90% of the total catch on an annual basis) in each sector using the methodology described in Russo et al. (2018). LPUE is measured in kg of landings per hour of trawling and length of the fishing vessel and is the index by which a given amount of fishing effort can be used to estimate the corresponding catches (or landings).

SMART modelling approach

The obtained LPUEs were used to estimate the expected LV (revenues of the fishing activity) associated with both actual and simulated vessel-specific fishing effort patterns using the SMART model (Russo et al. 2014a, D'Andrea et al. 2020) and the mean prices per species/kg. The SMART model is a tool for assessing bioeconomic evaluation under different fisheries management scenarios. The model is based on the following main assumptions:

- For each fishing vessel v and time t, it is possible to estimate the *Landings* and *Landings value* starting from spatial LPUEs and spatial effort. Here, *Landings* referred only to the amount of commercial fraction, assuming that the discards are negligible. In the meantime, *Costs* can be estimated, in parallel to landings, from the spatial effort pattern.
- Each vessel operates to maximize *Profits* (i.e. the difference between *Landing value* and *Costs*) over a given time frame (e.g. monthly). Here, *Profits* are defined as the difference between *Landings value* (i.e. revenues) and *Costs*.

Specifically, SMART reconstructs the spatial and temporal flows of landings, from fishing grounds (cells of the grid) to commercial ports, as follows:

The expected *Landings* (L) in kg obtained in cell c, for the species s, at time t, from vessel v, is as follows:

$$L_{c,t,s,v} = LPUE_{c,t,s} \times Effort_{c,t,v},$$

where $LPUE_{c,t,s}$ is the LPUE in cell c, at time t, for species s, and $Effort_{c,t,v}$ is the fishing effort of vessel v in cell c at time t.

The expected *Landing value* ($LV_{s,c,v,t}$) in Euro per species, cell, vessel, and time is as follows:

$$LV_{c,t,s,v} = L_{c,t,s,v} \times Price_s,$$

where $Price_s$ is the price, in Euro per kg of species s.

The corresponding aggregated *Landing value* ($LV_{v,t}$) of vessel v during the time t is computed as follows:

$$LV_{v,t} = \sum_{c=1}^{C} \sum_{s=1}^{S} LV_{c,t,s,v}.$$

Summing the value of $LV_{s,c,v,t}$ for all the S species and C cells exploited by the vessel v during the time t.

In parallel, *Costs* are estimated for each vessel v as the sum of two components: *Fuel Costs* (FC) and *Additional Costs* (AC). The *Fuel Costs* depend on how much and where each vessel allocates fishing effort and can be separated into *CostEffort* (fuel consumption during fishing activity) and *CostSteaming* (consumption during navigation to and from fishing grounds).

Hence, FC (in Euros) for vessel v in cell c at time t is obtained as follows:

$$FC_{v,t} = \sum_{c=1}^{C} CostEffort_{v,c,t} + CostSteaming_{v,t}.$$

$CostEffort_{v,c,t}$ is the product of the amount of effort (in hours) allocated by the vessel in the cell c, the mean fuel consumption parameter hFC (in l/h of fishing, according to vessel size), and the price of fuel (FP in Euro/l):

$$CostEffort_{v,c,t} = EffortTime_{v,c,t} \times hFC_v \times FP.$$

Sala et al. (2022) report the value of the hFC for bottom otter trawlers operating in the Italian waters as a function of their vessel speed during towing activities.

$CostSteaming_{v,c,t}$ is computed, for each fishing vessel v during the time t, starting from its fishing effort pattern. First of all, the distance d_c (in km) between each cell c in which the vessel v operates during the time t and the starting harbour is computed. This returns a vector D of distances, from which a weighted average is computed using the amount of effort in each cell as weight. In this way, from the effort allocated during the time t, it is possible to obtain a value of d_t, which summarizes the mean distance of the fishing grounds from the harbour. This value d_t is used to estimate (knowing the average steaming speed of the vessel v), the corresponding SteamingTime (ST_t). Finally, the *CostSteaming* over the entire time t is computed as the product of twice the value of the $SteamingTime_{v,t}$ (to consider daily round trip to and from fishing grounds), by the number of *Fishing Trips* ($FT_{v,t}$) of vessel v during the time t, the fuel consumption (hFC_v) of the vessel during its steaming activity (in l/h of fishing, according to vessel size) and the price of fuel (FP in Euro/l):

$$CostSteaming_{v,t} = 2 \times SteamingTime_{v,t} \times FT_{v,t} \times hFC_v \times FP.$$

Note that the parameter hFC_v in both $CostEffort$ and $CostSteaming$ is formarily the same for a given vessel. Still, it takes different values depending on the speeds during the fishing and sailing phases, respectively, according to Sala et al. (2022). The value of $FT_{v,t}$ was calculated as the monthly average of the years considered, for each vessel in each case study.

One of the advantages of this approach is that it allows new patterns of fishing effort to be simulated for each vessel v and time t and, thus, to obtain from them both $CostEffort$ and $CostSteaming$.

The expected *Additional costs* (AC in Euro), for vessel v during time t, are defined as follows:

$$AC_{v,t} = FixedCosts_{v,t} + VariableCost_{v,t},$$

where $FixedCost_{v,t}$ is the maintenance of vessel, gear, and insurance during time t; and $VariableCost_{v,t}$ concerns costs tied to the landed quantity of fish from taxes or commercialization costs. $FixedCost_{v,t}$ values were obtained, for each vessel, from the values contained in the Annual Economic Report (European Commission: Joint Research Centre et al. 2023) for the different segments of the fleets considered.

Finally, *Landing value* and *Costs* (including both *Fuel Costs* and *Additional Costs*) were used to calculate the *Profits* (in Euro) for each vessel v during the time t as follows:

$$Profits_{v,t} = LV_{v,t} - (FC_{v,t} + AC_{v,t}).$$

Then, these values were aggregated by fleet and year.

The goodness-of-fit of the bioeconomic model returned by SMART was tested by comparing the seasonal landings values predicted by SMART for each vessel/species with those observed. Moreover, the values returned by the SMART application for economic parameters (LV, costs, and profits) were compared with the official values available for the fishing segments in the Annual Economic Report of the European Commission and with yearly aggregated values of LV, costs, and profits for each year during the period 2017–2019 and each GSA in the case study. These data were provided by NISEA (http://www.nisea.eu/).

Two forms of validation were conducted for this purpose:

- A cross-validation at single vessel-level.
- A comparison with an external source of information represented by the yearly aggregated LV, costs and profits for each year during the period 2017–2019 and for each GSA in the case study.

In the first case, 80% of the vessels for each case study were randomly selected to estimate all the parameters listed above. The remaining 20% of vessels were used as a test dataset and their annual observed LV, costs and profits (average over the period 2017–2019) were compared with the corresponding prediction returned by SMART. In the second case, the predictions returned by SMART were aggregated by GSA (considering the membership of the grid cells in the different case studies) and compared with the reference values. The results of these checks are reported in Figs. S3 and S4. The above model was fitted to the data and successively used to test the different scenarios considered (see Section 2.5).

Identification of the core fishing grounds

The identification of core fishing grounds was achieved through the utilization of spatial economic features, specifically profits and LV. In accordance with the methodology proposed by Ban and Vincent (2009), the core fishing grounds in each case study were defined as the smallest area required to sustain 90% of current profits. This is analogous to the Marxan methodology employed in conservation planning (e.g. Fabbrizzi et al. 2023), whereby the least costly solution to an objective function is identified through the use of a simulated annealing algorithm. Marxan is an optimization technique that identifies multiple near-optimal solutions to maximize conservation interests while minimizing costs, subject to a set of predefined conservation targets. For each scenario, Marxan was executed 100 times with 1 000 000 iterations, resulting in two primary outputs: the optimal planning solution and the frequency of selection, corresponding to the number of times a planning unit (group of cells) was selected over the 100 iterations. This approach identified the specific set of cells corresponding to 90% of economic values while minimizing spatial fragmentation, thus delineating the core fishing grounds. This modelling approach was inspired by the work done within the *Workshop on Trade-offs between the Impact of Fisheries on Seafloor Habitats and their Landings and Economic Performance* (WKTRADE) (ICES 2024b). Specifically, the procedure outlined at https://github.com/ices-eg/WKTRADE3 employs integer linear programming with the 'prioritizr' package in R (Hanson et al. 2023).

Simulation-based evaluation of displacement for different scenarios

The potential effects of various spatial and/or temporal-based management scenarios were investigated by simulating and optimizing the new fishing effort pattern of each vessel (in terms of number of cells exploited or closed to trawl fishing), starting from the result of the SMART model, which was also utilized to conduct the simulations. This approach took advantage of an individual-based model to explore the potential displacement of the effort originally allocated in the area to be closed, through a Bayesian approach (Russo et al. 2019b).

A single run of SMART proceeds with the following steps, replicated for each individual vessel in each month:

1. Defines the set of potentially usable cells as the set of cells used by all vessels belonging to the same port under consideration.

Table 1. Spatial extent of the potential area for trawl fishing.

Sector	GSAs	Total area of seafloor (in km^2) in the bathymetric range 0–1000m	Area (in km^2) actually exploited by bottom otter trawl fishing (mean 2017–2021)	Ratio (*Status quo*)
1 Western	9, 10, 11.1, and 11.2	92.7×10^3	68.6×10^3	0.73
2 Southern	12–16	156.2×10^3	84.7×10^3	0.54
3 Adriatic	17 and 18	134.6×10^3	88.7×10^3	0.65
4 Ionian	19	24.6×10^3	12.8×10^3	0.52

2. Calculates the proportion of total effort (fishing hours) per month allocated in each cell. These proportions represent a probability vector of effort allocation in the *status quo*.
3. Identifies the set of cells to be closed (depending on the scenario) and sets their probability equal to zero.
4. Generates a new probability vector, from the one defined previously, using the Monte Carlo method.
5. Uses this probability vector to allocate the total monthly effort (previously calculated) with respect to the cells.
6. Calculates (based on LPUEs) the corresponding landing, LV and CostEffort.
7. Uses the new effort pattern to update the d_t vector and then to compute CostSteaming.
8. Calculates new profits and considers whether to accept the new pattern or to discard it.

Step 8 requires some additional information. Because many scenarios involve an initial 'loss' of fishing grounds, the new profit values are often lower than those of the *status quo*. So, the assessment on the acceptability of the newly generated effort patterns is conducted on the average value of the profits obtained for the first 10 simulations. Thereafter, the new patterns are accepted only if the profits increase from the reference value, which is then progressively updated. For each month, the simulation process proceeds iteratively with the random extraction of a vessel, the generation and evaluation of a new pattern, and the eventual updating of profit values and effort and probability vectors (Step 4). The simulation ends for each individual vessel when its profits do not improve for 30 successive simulations. In this way, individual vessels gradually 'exit' the simulation process, which ends when there are no more vessels to optimize. Ultimately, the output can be aggregated at fleet level to generate summary results.

Five different scenarios (Fig. S2) were considered for each sector: (1) permanent ban of bottom trawling in the existing GFCM fisheries restricted areas (FRAs), (2) fishing ban within 6 nautical miles from the coast, (3) fishing ban at depths >600 m, (4) >700 m, and (5) >800 m. Scenario 1 is based upon the most recent GFCM information (https://www.fao.org/gfcm/data/maps/fras/fr/#:~:text=A%20fisheries%20restricted%20area%20(FRA,habitats%20and%20deep%2Dsea%20ecosystems), while Scenarios 2–5 examine the extension of existing spatial restrictions further offshore (Scenario 2) and into deeper areas (Scenarios 3–5). It is important to note that these last three management scenarios (Scenarios 3–5), are under evaluation in the framework of the activities carried out by the GFCM. With regard to Scenario 1, it is important to specify that, for simplicity's sake, the entire area of each FRA was considered subject to permanent closure for trawling, without distinction between subareas.

Currently, trawling bans in the Mediterranean Sea are set at a distance of 3 nautical miles from the coast (or where depth is <50 m) and over 1000 m. If the limitations of the proposed scenarios were applied to the investigated areas and the fishing effort kept at the same present level, the interested vessels would need to consider costs, revenues, and economic sustainability of their fishing activity due to the reallocation of effort. For each scenario, 100 simulation runs were conducted, and the effects on fishery displacement pattern and relative landings were evaluated, including the value of profits (i.e. is assumed to be the best proxy for the economic performance of the fleet). Scenarios were conducted for areas up to a depth of 1000 m, beyond which trawling is prohibited in the Mediterranean.

It is important to clarify that the spatial model applied in this paper does not consider the changes in the biomasses of the exploited species and how they affect the spatial LPUE. Consequently, the effects of the scenarios that have been explored are to be considered only relative to the time in which the spatial closures are adopted.

Results

Bottom otter trawling in the four case studies

The four case studies represent diverse Mediterranean regions with differing ecological and environmental characteristics, and their respective fisheries exploitation strategies reflect these variations (Table 1). The Western sector represents the basin with the highest proportion (73%) of the available surface area that is exploited by trawl fishing, followed by the Adriatic sector (65%). The ratio is lower and similar in the Southern (54%) and Ionian sectors (52%), where almost half of the seafloor is not affected by trawl fishing.

Core fishing ground analysis

Core fishing grounds in the Western sector (Fig. 3A) were found to be most abundant along the coast in the shallower part of the shelf (50–150 m) and in the slope between 400 and 600 m. In the Southern sector (Fig. 3B), core fishing grounds were mainly found in the central part of the spatial domain between 500 and 750 m and in the coastal shelf (50–250 m). In the Adriatic sector (Fig. 3C), core fishing grounds were widely distributed along the Italian and Croatian coasts at depths of 50–200 m. In this basin, core fishing areas in the deeper strata are of marginal importance. The pattern is completely different in the Ionian sector (Fig. 3D), where core fishing grounds are distributed throughout the entire exploitable bathymetric range, with a peak between 100 and 200 m. The rarefaction curves describing the cumulative economic trends for the four case studies are depicted in Fig. 4. The cumulative curves of profits are always steeper than those of LV, but this difference is less pronounced for the Ionian sector. The values of the in-

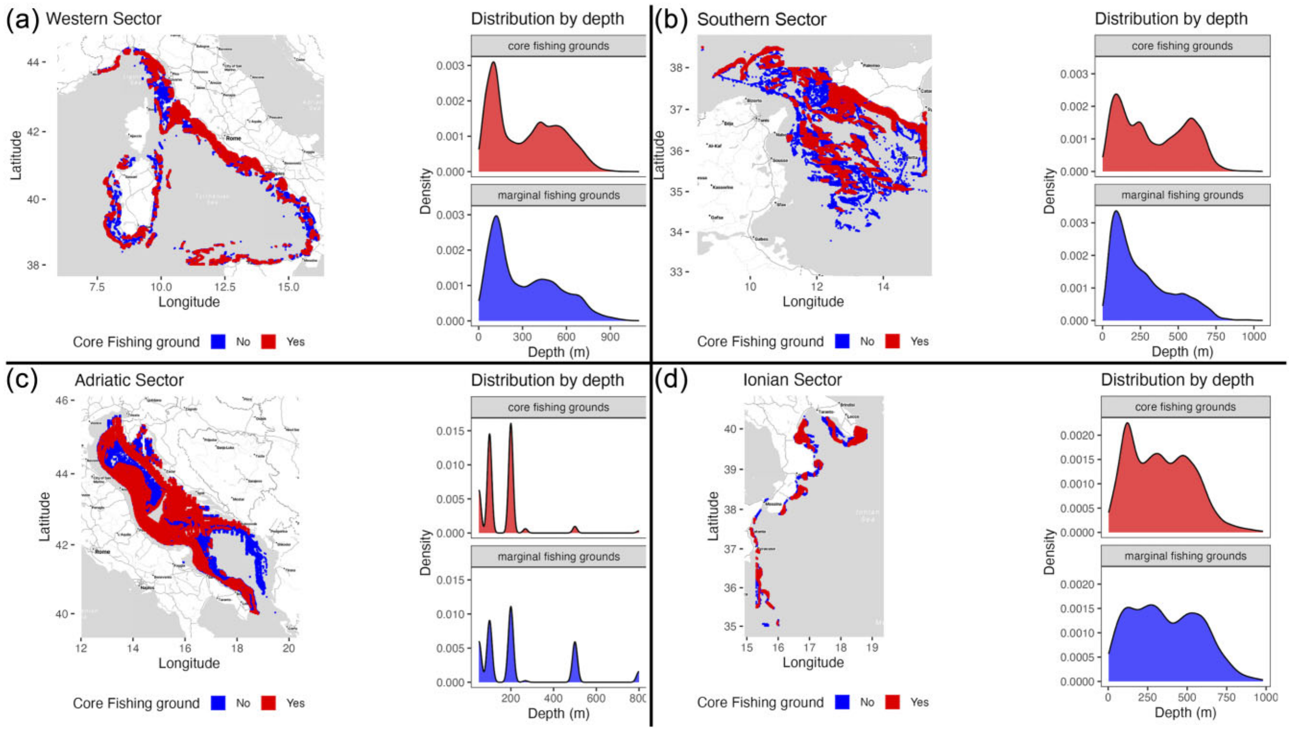

Figure 3. Maps of the core and marginal fishing grounds and their bathymetric distribution for the four case studies, presented in separate panels. Core fishing grounds were defined as the minimum area required to maintain 90% of the total profits.

tercepts on the *x*-axis, which indicates the percentage (%) of the presently exploited area (mean over the years 2017–2021) that is needed to achieve the 80% or 90% targets of profits and LV, evidenced a similar pattern in all the case studies: the profits curve is always above the LV curve. This effect can be linked to the presence of cells with negative profits values. Hence (Fig. 4 and Table 2), 80% of the total LV is reached exploiting from ~40% (Southern and Adriatic sectors for the Croatian fleet) to ~50% (Adriatic sector for the Italian fleet) of the fished area. This range expands between ~55% (Adriatic sector for the Croatian fleet) and ~66% (Western sector) when the target increases to 90% of the total LV. All these values are lower if the targets are defined as 80% or 90% of profits instead of the LV (Table 2). In this case, 90% of profits could be obtained by exploiting 48% (Adriatic sector for the Croatian fleet) and 58% (Western sector) of the fished area in the *status quo*.

Simulation-based evaluation of different scenarios

Considering the complexity of the results, individual subsections are dedicated to the case studies. For the Adriatic sector, results are presented by country, for both Italy and Croatia. Table 3 shows the relative contribution of the areas defined in the different simulated scenarios to the total annual fishing effort, evidencing that:

- Trawling bans over 600, 700, or 800 m capture from 20% to 30% of the total effort (in terms of area exploited by fisheries) in the Western and Ionian sectors, whereas this value is smaller than 12% in the Southern sector and even smaller in the Adriatic sector (<3%).
- FRAs account for around 24% of the exploited area (for the Italian fleet) in the Adriatic sector, whereas this value is always lower than 6% in the other case studies.
- The coastal area (within 6 nm) captures >40% of the total area exploited by fisheries in the Western sector, and 34% in the Ionian sector. In these two case studies, the relative importance of this area is much higher than in the Southern sector (<15%) and Adriatic sector (<10%).

Case study 1—Western sector

In the Western sector, the coastal grounds within 6 nm corresponded to ~40% of the total trawling area (Table 3). The 6 nm ban scenario pushed the fishing fleet towards deeper waters far from the coastline (Fig. 5A). The measures regarding the closure of areas with depths over 600, 700, and 800 m affected a significant portion of the northern part of the sector, as well as the seas around Sardinia (31.7%, 24.1%, and 19.1%, respectively of the area available to trawlers). In the scenarios where the bathymetry determines the area subjected to regulation, fishing vessels would be forced to leave deeper fishing grounds and move closer to the coast. The effects are stronger as the banned area extends, so the changes in the redistribution of effort are predicted to be more significant in the case of a ban of over 600 m. The FRA scenario in the Western sector contributes to a decrease in the available fishing area of 2.1%. This scenario implies the closure of a collection of several areas of small extent, and the model does not predict significant changes in the overall redistribution of effort (Fig. 5A). The landing species composition changed due to the application of the different scenarios. In particular, the 6 nm ban scenario significantly affected the landing's species composition. SMART predicted an increase in catches for crustacean

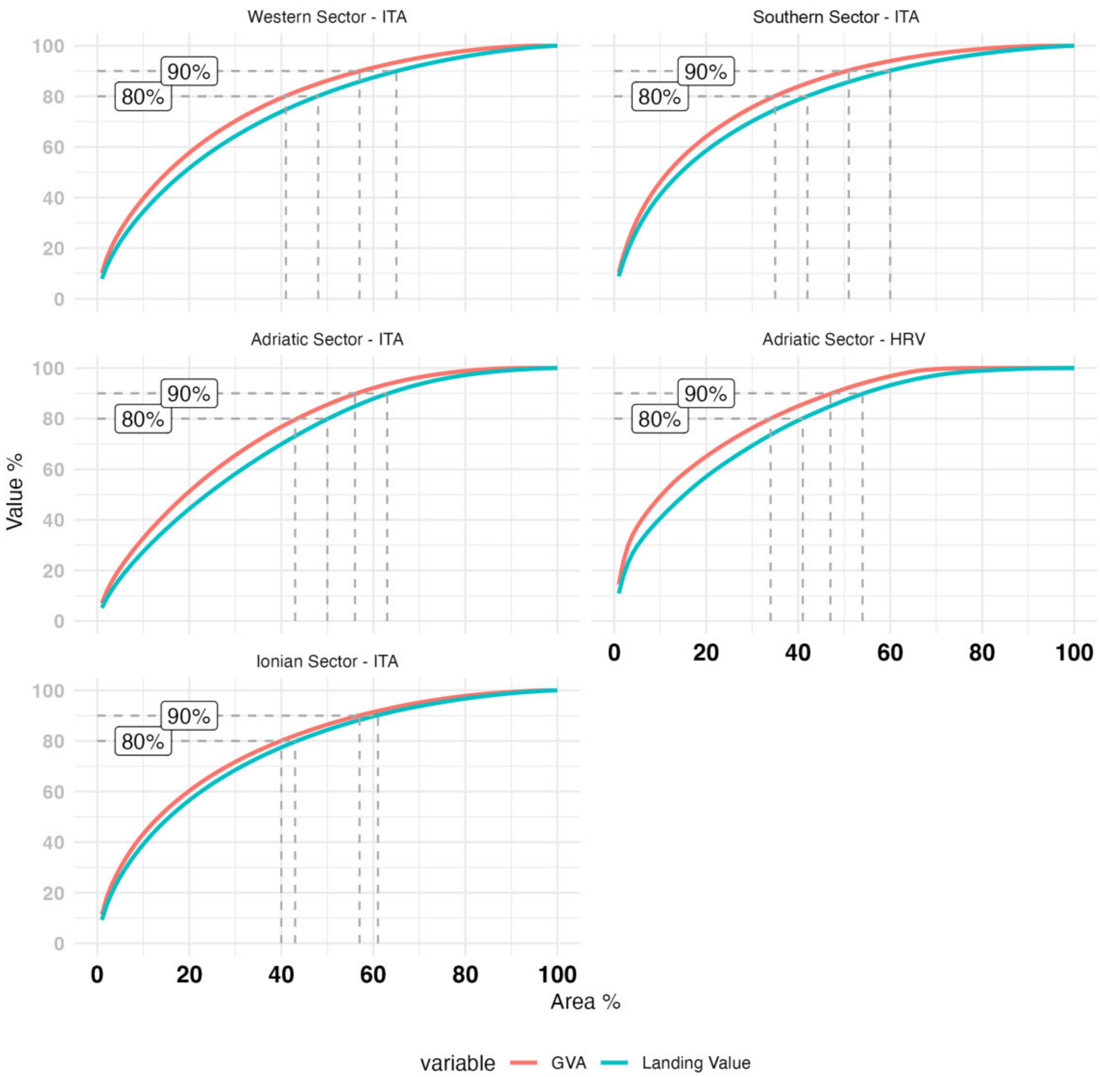

Figure 4. Patterns of cumulative economic indicators (LV and profits) for the four sectors. Dashed lines indicate the percentage of exploited areas with respect to 80% and 90% of the two economic indicators and allow to identify the corresponding % of presently exploited areas (*x*-axis).

Table 2. Value of the intercepts corresponding to the 80% and 90% targets of total LV and GVA, for each case study. Details by country are provided for the Adriatic Sea.

Case study	Country	LV		GVA	
		Target 80%	Target 90%	Target 80%	Target 90%
1 Western sector	ITA	48%	66%	41%	58%
2 Southern sector	ITA	42%	60%	35%	51%
3 Adriatic sector	HRV	41%	55%	34%	48%
3 Adriatic sector	ITA	51%	64%	44%	57%
4 Ionian sector	ITA	44%	61%	40%	57%

Table 3. Results of the simulated scenarios as the percentage of the area unavailable for fishing in comparison to the *status quo*, for each case study.

Case study	Country	% of the total area unavailable to fishing with respect to the *status quo*				
		Ban over 600 m	Ban over 700 m	Ban over 800 m	Ban 6 nm	FRA
1 Western sector	**ITA**	**31.7**	**24.1**	**19.1**	**41.9**	**2.1**
2 Southern sector	**ITA**	**11.1**	**5.8**	**3**	**14**	**5.2**
3 Adriatic sector	**HRV**	**5.6**	**5.6**	**2.3**	**67.7**	**10.5**
3 Adriatic sector	**ITA**	**2.7**	**2.7**	**0.1**	**8.1**	**2.7**
4 Ionian sector	**ITA**	**36.2**	**27.9**	**20.2**	**34**	**3.4**

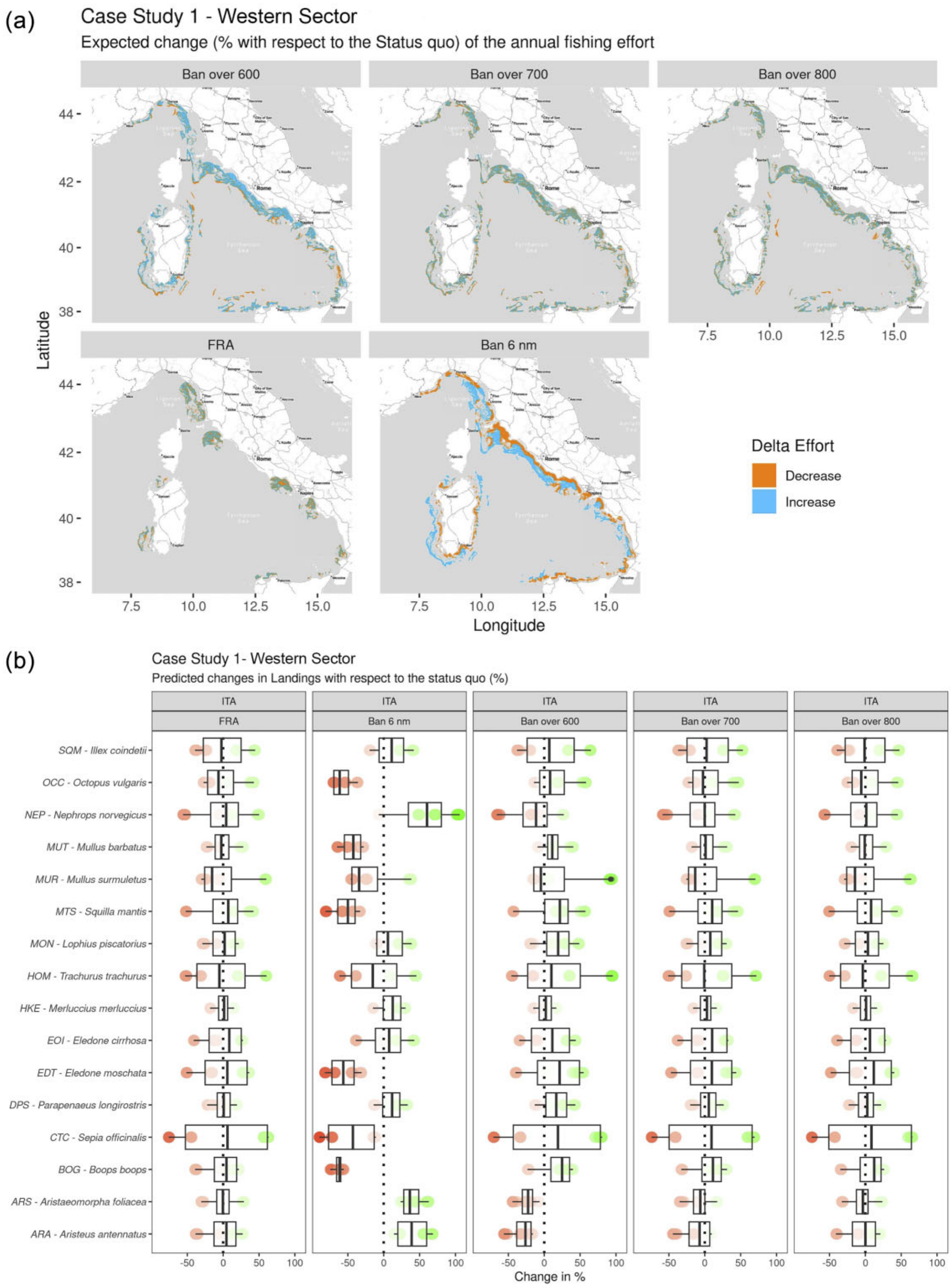

Figure 5. Panel A: expected change in fishing effort (% with respect to the values observed in the *status quo*) as a consequence of the application of different management scenarios in the Western sector. Cells where an absolute percentage change in fishing effort (compared to *status quo*) >10% is expected are shown . Panel B: boxplots representing the predicted changes in landing species composition (% compared to the *status quo*) as a consequence of the application of different management scenarios in the Western sector.

species such as the Norway lobster *Nephrops norvegicus* (NEP), the Blue and red shrimp *Aristeus antennatus* (ARA), the Giant red shrimp *Aristaeomorpha foliacea* (ARS), and the Deep-water rose shrimp *Parapenaeus longirostris* (DPS), while landings of the Common octopus *Octopus vulgaris* (OCC), the Red mullet *Mullus barbatus* (MUT), the Surmullet *Mullus surmuletus* (MUR), the Spottail mantis shrimp *Squilla mantis* MTS, the Musky octopus *Eledone moschata* (EDT), the Common cuttlefish *Sepia officinalis* (CTC), and the Bogue *Boops boops* (BOG) significantly declined. As previously noted for the bathymetric restrictions, it is possible to observe that the effects are more significant as the affected area increases. Indeed, the most significant impacts were predicted for the ban over 600 m, where a relevant decrease in catches of deep-sea crustaceans (the Norway lobster, Blue and red shrimp, and Giant red shrimp) is expected. Regarding the FRAs, little or negligible changes affected the landing's species composition.

Case study 2—Southern sector

In the Southern sector, the 6 nm ban resulted in the closure of 14% of the area available to trawling activities (Table 3). This measure affected the shallow bottoms extending along the southern coast of Sicily and a significant portion of the continental shelf surrounding the island of Lampedusa. Fishing vessels would be forced to move towards deeper grounds in the middle of the Strait of Sicily, with characteristic areas >800 m depth between the relatively shallow continental shelf that extends from Sicily to Tunisia. These areas represented only 3% of the total area. Closing up to 700 and 600 m resulted in a closure of 5.8% and 11.1% of the area available for fishing activities. In this context, these activities are expected to be reallocated towards waters of intermediate depths, mainly ranging from 300 and 500 m, and vessels would be forced to leave deep-water grounds close to the deep trenches located in the middle of the Strait. The FRA scenario implied the closure of two important areas with shallow bottoms: a portion of the continental shelf along the southern coast of Sicily and a large portion of the Adventure Bank (West Sicily). This scenario affected 5.2% of the exploited area (Fig. 6A).

The 6 nm ban scenario forecasted a decrease in the landings of several demersal resources that are fished along the coast, such as the Common octopus, the Red mullet, the Spottail mantis shrimp, the Musky octopus, the Common cuttlefish, and the Bogue. A slight increase in catches for the Norway lobster and the Deep-water rose shrimp is expected. As for the bathymetric bans, the only significant differences in the landings' species composition could be predicted for the ban over 600 m: the application of this scenario led to an increase in catches to a greater or lesser extent for all species with the exception of the Blue and red shrimp and of the Giant red shrimp, which showed a slight decrease. The closure of the FRA areas in the Southern sector was not expected to bring significant alterations to the composition of landings (Fig. 6B).

Case study 3—Adriatic sector

The 6 nm closure scenario had distinct effects on the Italian and Croatian fleets due to significant coastline morphological differences. Italy has a nearly straight shoreline in this sector, and only ~8% of the waters were impacted by the 6 nm restriction (Table 3). In contrast, the jagged Croatian coast has an irregular profile, and about a thousand coastal islands are located off the mainland. A potential ban within 6 nm off the coast led to the closure of ~68% of the Croatian waters to fishing activities (Table 3). Concerning the closure of the areas deeper than 600, 700, and 800 m, a reduction in the available area of 2.7%, 2.7%, and 0.1% was predicted for the Italian fleet respectively, and of 5.6%, 5.6%, and 2.3% for the Croatian fleet, respectively. For the Italian fleet, the FRA scenario meant the closure of 2.7% of the area available for trawling. As for the Croatian fleet, the FRA scenario made up 10.5% of the case study area (Fig. 7A). Concerning the bathymetric bans (600–700–800 m), significant changes in the composition of catches occurred just for the Croatian fleet, where the Norway lobster catches decreased slightly. An important decrease, in terms of catches, is forecasted in the case of the 6 nm ban for the Croatian fleet. Almost all of the considered species are expected to be negatively affected by the regulation except the Giant red shrimp and Blue and red shrimp. No significant changes in the composition of the catches were found in the FRA scenario (Fig. 7B).

Case study 4—Ionian sector

In the Ionian sector, the 6 nm ban resulted in a closure of 34% of the area exploitable by trawlers (Table 3). The closure of fishing activities to depths over 600, 700, and 800 m implied significant decreases in the area available to fisheries: 36.2%, 27.9%, and 20.2%, respectively. A single FRA is considered for this case study, located on the continental slope east of the Taranto Canyon, covering 3.4% of the area currently exploited (Fig. 8A). The closure of the 6 nm resulted in a decrease in catches for most of the coastal species [i.e. Common octopus, Red mullet, the Spottail mantis shrimp, the Atlantic horse mackerel *Trachurus trachurus* (HOM), the European hake *Merluccius merluccius* (HKE), the Deep-water rose shrimp, and the Bogue]. Other significant changes in the species composition of landings were not observed in the evaluated scenarios (Fig. 8B). Overall, a decrease of yield of the Blue and red shrimp are predicted in all simulated scenarios.

Impact on profits

As for the overall impact on profits of the considered management scenarios, for the Western sector, an opposite effect can be observed for the coastal and bathymetric bans. Applying the 6 nm ban led to an increase in profits of ~5% (Fig. 9). In contrast, the management scenarios involving fishing bans over 600, 700, and 800 m implied a decrease in profits. The economic outcomes are more significant as the area interested in the regulation extends, and the impact on profits increases from the 800 to the 600 m ban. As previously reported, the FRA scenario affected only a small portion of the total area, and little variation is expected for the economic variable. Regarding the Southern sector, it was possible to predict the same outcomes as the ones seen for the Western Mediterranean Sea, albeit with an even greater magnitude. An increase in profits of >10% is indeed expected for the 6 nm ban, as well as a decrease for the bathymetric bans, with a larger size for the ban over 600 m (corresponding to ~25% decrease). For the FRA scenario, a slight decrease in profits is expected. For the Adriatic sector, the application of the coastal ban made fishing activities in Croatian waters highly unprofitable (~65% decrease). On the other hand, this scenario had a positive economic impact on the Italian fleet (~15% increase). For the bathymetric bans, there was a slight positive increase in profits for the Italian fleet, while only the 600 m ban had positive values for the Croatian one.

In the Ionian sector, the impact on the economic scenario was predicted to be opposite to that observed for the Western and Southern sectors. The application of the 6 nm ban led to a decrease in profits (~ −15%), while an increase in this variable was observed for the bans over 600, 700, and 800 m. As for the other case studies, the impacts were greater as the area of interest increased, so the ban over 600 m had the most important economic consequences. Although the area involved in the FRA scenario is quite small, a significant decrease in profits was predicted for this scenario (Fig. 9).

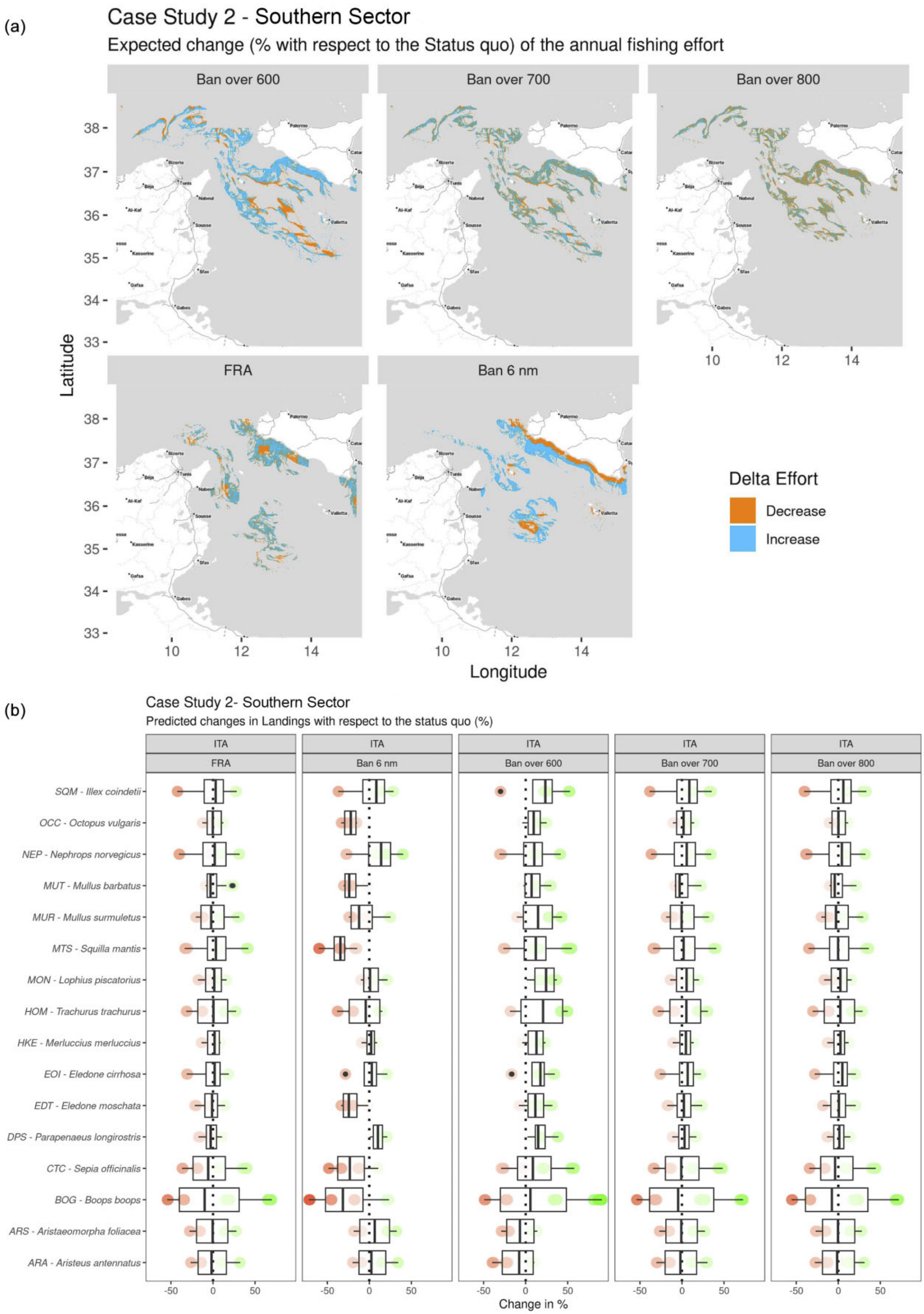

Figure 6. Panel A: expected change in fishing effort (% of area compared to the *status quo*) as a consequence of the application of different management scenarios in the Southern sector. Cells where an absolute percentage change in fishing effort (compared to *status quo*) >10% is expected are shown . Panel B: boxplots representing the predicted changes in landing species composition (% compared to the *status quo*) as a consequence of the application of different management scenarios in the Southern sector.

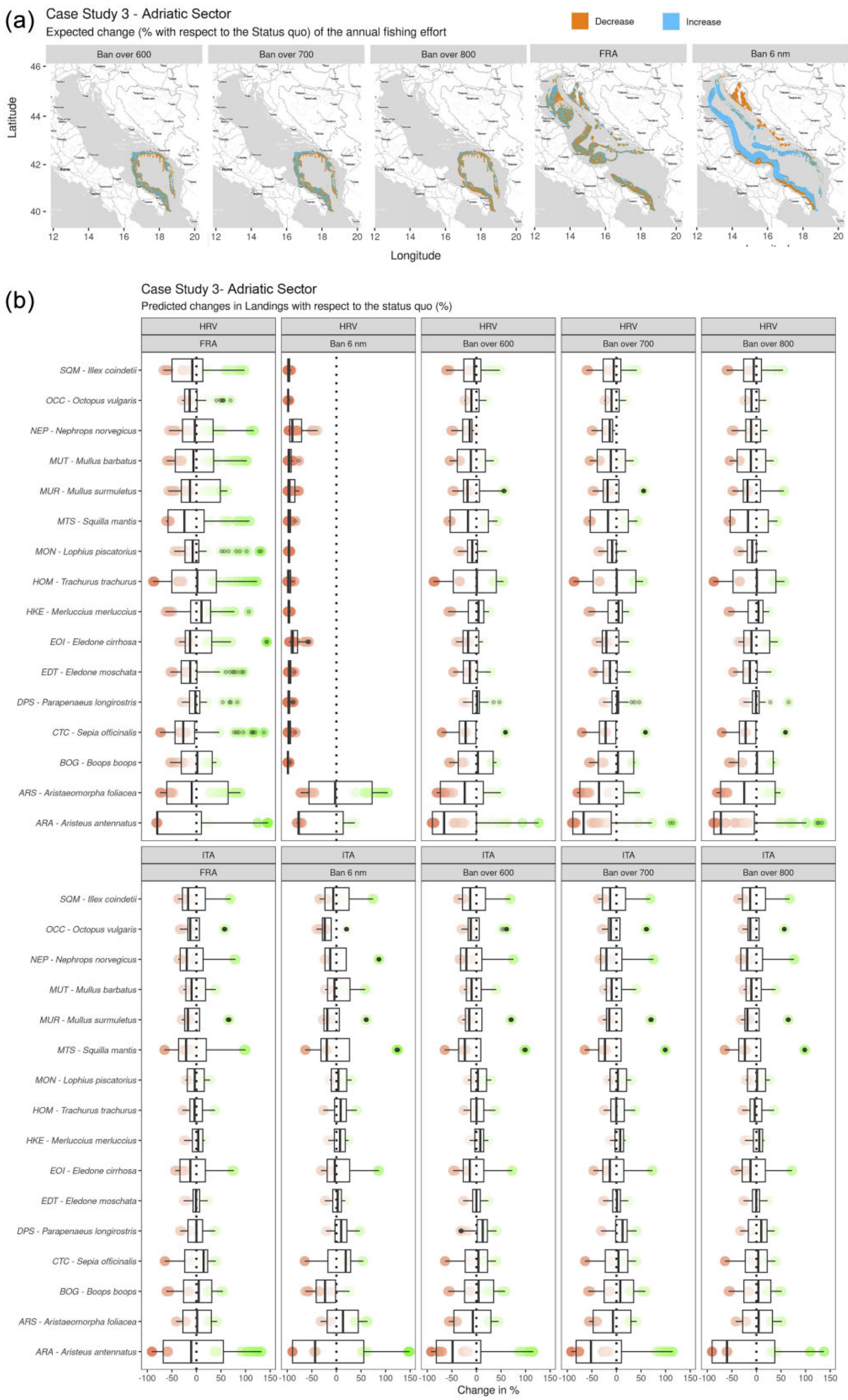

Figure 7. Panel A: expected change in fishing effort (% of area compared to the *status quo*) as a consequence of the application of different management scenarios in the Adriatic sector. Cells where an absolute percentage change in fishing effort (compared to *status quo*) >10% is expected are shown. Panel B: boxplots representing the predicted changes in landing species composition (% compared to the *status quo*) as a consequence of the application of different management scenarios in the Adriatic sector (HRV: Croatia; ITA: Italy).

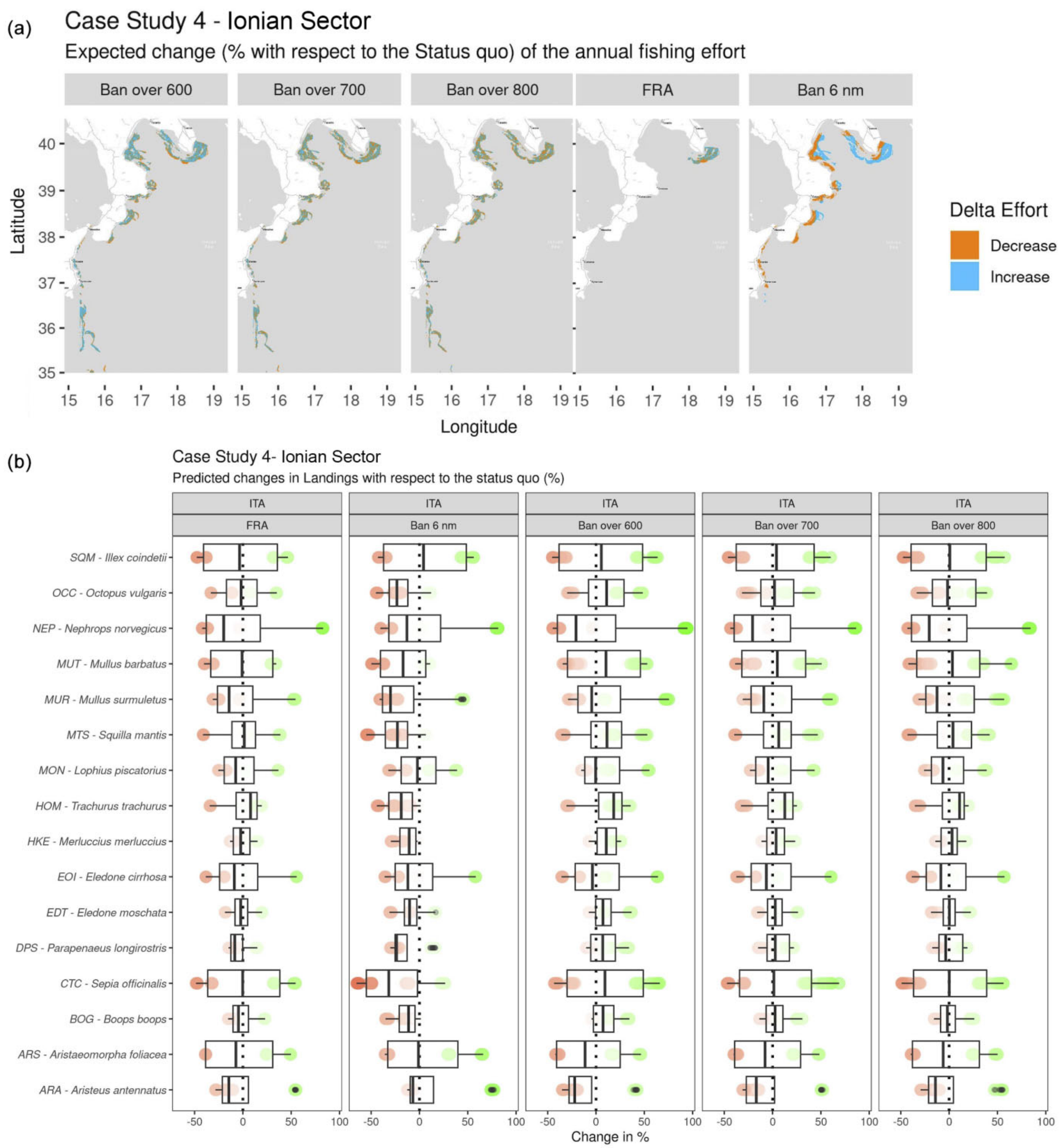

Figure 8. Panel A: expected change in fishing effort (% of area compared to the *status quo*) as a consequence of the application of different management scenarios in the Ionian sector. Cells where an absolute percentage change in fishing effort (compared to *status quo*) >10% is expected are shown. Panel B: boxplots representing the predicted changes in landing species composition (% compared to the *status quo*) as a consequence of the application of different management scenarios in the Ionian sector.

Discussion

This study constitutes the first spatial analysis of all four basins around the Italian peninsula and the first assessment of trawl fisheries' core and marginal fishing grounds.

Considering the study area as a whole, the results indicate that restricting the distribution of trawl fishing to ∼60% of the presently exploited area, it would be possible to maintain up to 90% of the current LV and profits. These results are conceptually consistent with those obtained in ICES when considering LV for the North Sea, whereas it seems that, in the Mediterranean Sea, the core fishing grounds cover a larger area (60%) compared to the 40% estimated for the North Sea (ICES 2024b). However, regardless of the threshold value, the present results indicate (as has been the case previously

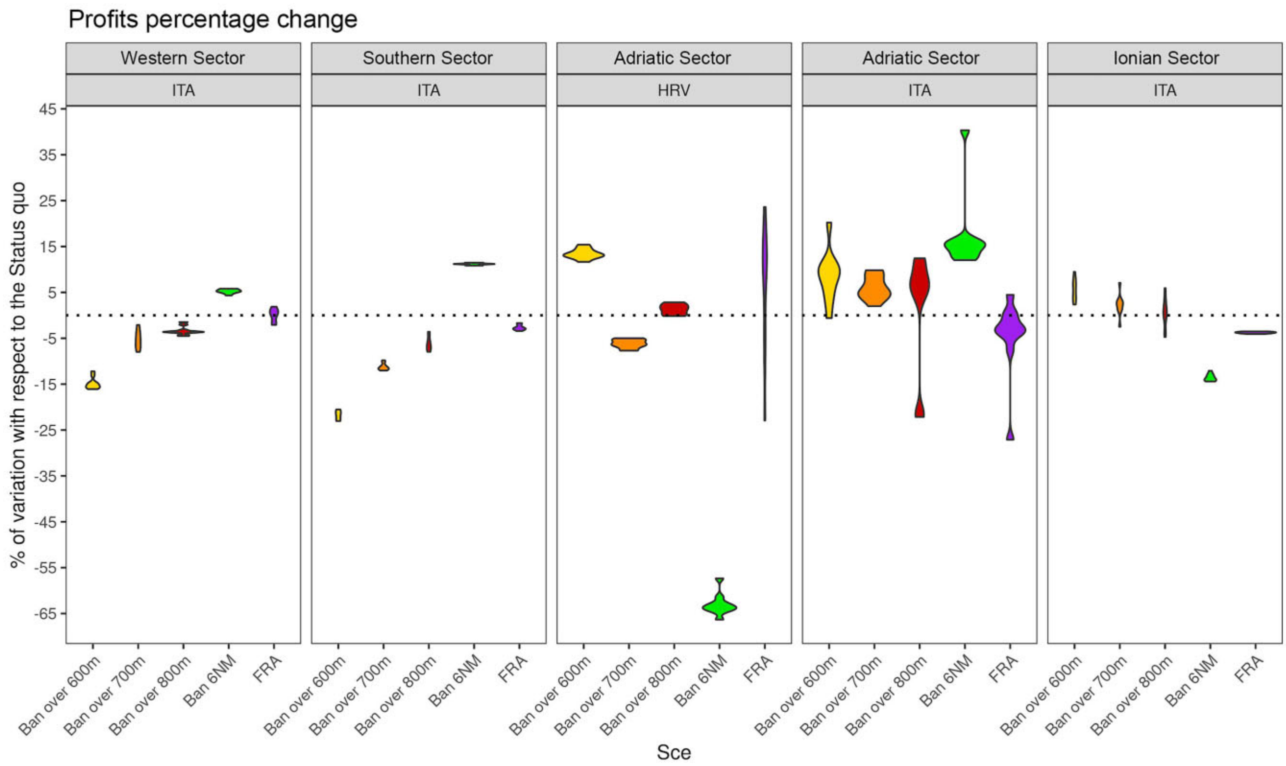

Figure 9. Violin plot representing the profits percentage change compared to the *status quo*. The SMART model returned these patterns and represents the distribution over 10 simulations.

for Greater North Sea, Celtic Seas, and Bay of Biscay and the Iberian Coast areas) that the area exploited by bottom trawling could be significantly reduced with limited economic losses.

The second part of this study concerns the exploration of different spatial-based management scenarios and the results highlight the difficulty of identifying a measure that may prove effective across all the case studies. Given the high heterogeneity of the Mediterranean Sea, the distribution of the core fishing grounds with respect to depth profiles reflects the different morphological and ecological characteristics of the Western, Southern, Adriatic, and Ionian sectors. The shallowest fishing grounds (50–200 m depth) dominate in the Adriatic Sea, while the deepest grounds (400–600 m) are important in the Western and Southern sectors. The Ionian sector is the only case of a balanced situation in which the presence of core fishing grounds smoothly decreases with depth. Indeed, in this work, the application of the same spatial closures was observed to have different consequences in the different regions. In the Western sector, important (core) fishing grounds are found on both the continental shelves and slopes. Shelf areas, albeit limited in their extension, are important for several fisheries targeting demersal species such as the Horned octopus (EOI), the European hake (HKE), and the Red mullet (MUT) (Cataudella and Spagnolo 2011). In the meantime, along the coasts of Liguria, Calabria, and Sicily, sea bottoms reach considerable depths just a few miles off the coast. In these areas, several fishing fleets target deep-sea crustaceans. These latter resources represent an important source of profit. This is likely the reason for the positive economic impact of the 6 nm ban for this case study: fishing fleets would be reallocated towards productive deep-sea fishing grounds not too far from the coastline, and hence reachable with little additional fuel consumption. In contrast, denying access to these deep areas by imposing bathymetry-dependent restrictions would cause a drop in the overall profits; a drop of ∼15% in profits was predicted for the ban over 600 m scenario, while the ban over 800 m implied a slight loss in profits of ∼3%. The Southern sector mainly concerns the Strait of Sicily, one of the most productive areas for demersal fisheries of the Mediterranean (Vasconcellos and Ünal 2022). Bottom trawling is widespread across the Strait, targeting the Deep-water rose shrimp (*P. longirostris*) as the main species, which represents ∼50% of the total landings of the Italian fleet. The European hake, the Red mullet, and the Giant red shrimp are also highly represented in landings from this region (Russo et al. 2019a). The economic importance of Deep-water rose shrimp is underlined by the positive impact on profits returned by applying the 6 nm ban. However, the implementation of this scenario would push the trawling fleets away from the shelves and towards the slopes along the southern coast of Sicily, exploited for Deep-water rose shrimp (Milisenda et al. 2017). The deep trenches located in the middle of the Strait host significant populations of the Giant red shrimp. These highly valuable crustaceans are fished over multiday fishing trips (Fiorentino et al. 2024). Given the high value of this fishery, closing these deep-water fishing grounds through the application of bathymetry-dependent bans would negatively impact the overall economic scenario, with a significant loss of ∼25% in the case of the ban over 600 m. Notwithstanding the environmental and ecological differences, similar economic responses to the analysed scenarios could be predicted in both the Western and Southern sectors. The Adriatic Sea is characterized by shallow waters, with higher depths located only in the southernmost areas. Owing to the peculiar morphology of the seafloor, bottom trawling is by far the most common fishing method used, and it is almost homogeneously widespread across the whole area. The European hake is the most important demersal species in the Adriatic Sea in terms of catches and commercial value. Other important species include the Red mullet, the Spottail mantis shrimp, and the Deep-water rose shrimp (UNEP/MAP—SPA/RAC 2021). As previously reported, large differences between the fisheries operating on the Italian and Croatian coasts could be observed. Applying the 6 nm ban for the Croatian fleet had the most dramatic consequences among all of the scenarios examined in this work. Indeed, it would lead to a decrease in the area available to trawlers of ∼68% and the overall loss in profits would be around ∼65%. This is because each of the 1246 islands located off this country's coasts would virtually generate a restricted zone around it. The effects can also be observed by looking at the sudden drop in most species' catches. Implementing the same scenario would instead benefit the Italian fleet, with an increase in profits of ∼15%. When analysing this result, it should be kept in mind that a considerable portion of the area within the 3 nm along the Italian coast involved in this scenario is shallower than 50 m, hence trawling is already restricted here. The Ionian sector is characterized by the scarce extension of the continental shelf that runs along its coasts. The area available for trawling is quite small since the seafloor rapidly drops below 1000 m (Manca et al. 2006). Nevertheless, the narrow shelf is exploited for the Red mullet, the Striped red mullet, and the European hake. In the upper portions of the continental slope, trawlers catch the Deep water rose shrimp and the Norway lobster, while the Blue and red shrimp and the Giant red shrimp are fished at greater depths (Maiorano et al. 2010, Russo et al. 2017). The limited area available is the reason for the negative impact of the 6 nm ban for this case study. Indeed, the Ionian sector is also the only examined case study, where positive outcomes were predicted for the application of the bathymetry-dependent bans.

The economic outcome of the simulated scenarios, as predicted by the SMART model, was significantly different across the sectors. Certain species, such as deep-sea crustaceans, greatly impact the overall profit of a fishing fleet, and the closure of coastal areas (6 nm ban) was found to enhance profits by pushing fishing vessels to more distant areas, where these high-profit species can be fished. However, the 6 nm ban, in some case studies, would lead to the closure of the space available for trawling and hence to a decrease in overall profits. The FRA scenario was found to have generally less impact on the overall economic aspect, as the extent of the involved areas is small. As for the bathymetry-dependent bans, the economic consequences, whether positive or negative, were found to be more significant as the depth threshold was reduced; closures up to 600 m had a greater impact on fisheries than those at 800 m. Notwithstanding the specific features of the case studies that impose the adoption of tailored solutions, some spatial-based measures were observed to have generally similar impacts across the cases. For example, the application of the ban over 800 m would allow the protection of a significant portion of the deep-sea bottom including several deep-water coral indicators of vulnerable marine ecosystems, with relatively little economic impact. This is in agreement with the distribution of the core fishing grounds, scarcely represented in the bathymetry range from 800 to 1000 m. Moving the Mediterranean trawling bathymetry ban from 1000 to 800 m would harmonize it with EU regulation for the Northeast Atlantic, with likely little overall economic consequences, and could help to achieve the protection of the 30% of EU seas, as defined by the EU Biodiversity Strategy (EU Commission 2020). Depth restriction-based management measures would also help achieve spatial protection goals for specific MSFD BHTs (e.g. for the bathyal habitats; Paramana et al. 2024) and for specific species indicators of Vulnerable Marine Ecosystems (e.g. deep sea corals and sea pens) (Lauria et al. 2017, 2021, Georges et al. 2024), thus, taking into account additional elements of environmental sustainability.

This study aimed to harmonize spatial and bioeconomic assessments of bottom trawling across the EU, specifically aligning the EU Mediterranean Sea with the EU North Atlantic. The main goal was to identify the most effective management measures scenarios for reducing the impact of bottom trawling while ensuring bioeconomic sustainability. At the same time, this study attempted to overcome some limitations that still characterize the approach applied in the ICES area. In fact, profits were used instead of LV to take into account the costs (especially fuel costs) associated with fishing in areas with different distances from the coast. Finally, the SMART model was used to estimate the possible fit of the fleet in terms of displacement.

Several caveats need to be considered when interpreting the results presented in this study. First, our analysis did not examine the effects on population dynamics in the mid and long terms but focused instead on the immediate consequences of fishing effort redistribution. Future work should avoid the displacement of fleets from less to more exploited stocks, taking into account the current state of exploitation of demersal resources, in addition to the immediate economic effects of effort reallocation. The examination of population dynamics is feasible through the utilization of bespoke models that receive as an input ecological data concerning specific species. The SMART model can be used in this regard, and it has been applied in the Western and Adriatic sectors, in which long-term resource effects are integrated through a population dynamics model (Carlucci et al. 2022, STECF 2022, 2023). However, no similarly advanced applications of SMART exist for the other examined case studies. Therefore, we presented a minimal but consistent set of results for all areas. This does not rule out the possibility of future extensions of model applications that would allow for in-depth predictions of the possible management scenarios outcomes.

It is also important to note that in three of the case studies, only the Italian fleet was considered, while in the Adriatic case study, the Italian and Croatian fleets were taken into account. This is not a limitation in the case studies of the Western and Ionian sectors, where only the Italian fleet actually operates. As for the Adriatic, it is known that the combined fishing capacity of Slovenian, Montenegrin, and Albanian fleets only represents 3% of the basin's total (Trainito et al. 2013, EC JRC & EC STECF 2021). In contrast, the Southern sector did not include the North African coast. Historically, demersal fisheries exploit the waters off North Africa, where a broad continental shelf provides ideal conditions for trawling (Vasconcellos and Ünal 2022). However, our analysis only included fishing activity data from areas with available vessel tracking data, like AIS or VMS. Consequently, the actual fishing extent and pressure on biological resources could be underestimated, particularly as vessels from non-EU nations that share these resources were active in these waters. In regions where VMS and AIS data are limited, emerging technologies, such as remote sensing (Marsaglia et al. 2024), could fill data gaps and support fisheries management in a future perspective.

The different spatial-based management scenarios discussed in this work demonstrate that 'one size does not fit all'. In addition to universal measures, further combinations of strategies with national adaptations will be required (e.g. FRAs, MPAs, and spatial bans) to reach conservation targets, including those set by the MSFD and the new Nature Restoration Law, for the restoration of EU habitats. Taking into account redistribution of fishing effort would be critical to afford protection to habitats under consideration. Sala et al. (2022), looking at technological innovations, similarly concluded that no single *modus operandi* can solve all seabed impacts. A combination of different approaches to balance productive fisheries' needs with those of bottom integrity and biodiversity conservation may be the most effective way forward.

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Author contributions

A.S.: data curation, validation, visualization, writing - original draft, writing – review & editing; S.G.: data curation, validation, visualization, writing - original draft, writing – review & editing; M.C.: resources, validation, writing – review & editing; R.C.: resources, validation, writing – review & editing; M.D.: resources, validation, writing – review & editing; F.F.: resources, supervision, validation, writing – review & editing; M.C.F.: supervision, validation; G.G.: resources, validation, writing – review & editing; V.G.: writing – review & editing; I.I.: writing – review & editing; K.K.: writing – review & editing; V.L.: writing – review & editing; P.M.: validation, writing – review & editing; C.M.: validation, writing – review & editing; B.M.:, writing – review & editing; P.P.: funding acquisition, project administration, writing – review & editing; N.P.: writing – review & editing; T.P.: writing – review & editing; V.P.: writing – review & editing; writing – review & editing; M.P.: writing – review & editing; A.R.: writing – review & editing; F.R.: writing – review & editing; E.C.S.: data curation, formal analyses, writing – review & editing; G.S.: writing – review & editing; C.S.: writing – review & editing; M.S.: writing – review & editing; N.S.: writing – review & editing; A.N.T.: writing – review & editing; A.Y.: writing – review & editing;, N.V.: resources, validation, writing – review & editing; S.R.: conceptualization, funding acquisition, methodology, project administration; T.R.: conceptualization, funding acquisition, investigation, data curation, formal analyses, methodology, project administration, visualization, writing – original draft.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Conflict of interest: None of the authors have conflicts of interest to declare.

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Data availability

Some of the primary data (VMS and logbooks) are protected by confidentiality. Others (MEDITS) are available to the Directorate-General for Maritime Affairs and Fisheries upon request. Metadata generated in the paper are available upon request to the corresponding author.

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