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Spatial planning for fisheries in the Northern Adriatic: working toward viable and sustainable fishing

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Abstract. Given the great overfishing of the demersal resources in the Northern Adriatic Sea (geographical sub-area [GSA] 17), along with the fishing pressure in marine habitats, evidence strongly supports the need to evaluate appropriate management approaches. Several fishing activities operate simultaneously in the area, and the need to minimize conflicts among them is also a social concern. We applied a spatially and temporally explicit fish and fisheries model to assess the impact of a suite of spatial plans suggested by practitioners that could reduce the pressure on the four demersal stocks of high commercial interest in the GSA 17 and that could promote space sharing between mutually exclusive activities. We found that excluding trawlers from some areas has lowered the effective fishing effort, resulting in some economic losses but providing benefit to the set netters. Not every simulated fishing vessel is impacted in the same way because some fishing communities experienced different economic opportunities, particularly when a 6-nautical mile buffer zone from the coast was implemented in the vicinity of important fishing grounds. Along this buffer zone, the four stocks were only slightly benefiting from the protection of the area and from fewer discards. In contrast, assuming a change in the ability of the population to disperse led to a large effect: Some fish became accessible in the coastal waters, therefore increasing the landings for range-limited fishers, but the discard rate of fish also increased, greatly impairing the long-term biomass levels. Our evaluation, however, confirmed that no effort is displaced onto vulnerable benthic habitats and to grounds not suitable for the continued operation of fishing. We conclude that the tested spatial management is helpful, but not sufficient to ensure sustainable fishing in the area, and therefore, additional management measures should be taken. Our test platform investigates the interaction between fish and fisheries at a fine geographical scale and simulates data for varying fishing methods and from different harbor communities in a unified framework. We contribute to the development of effective science-based inputs to facilitate policy improvement and better governance while evaluating trade-offs in fisheries management and marine spatial planning.

Key words: Adriatic Sea; bio-economic model; demersal fisheries; DISPLACE; ecosystem approach; essential fish habitats; fisheries management; fishing mortality; maritime spatial planning; shared fish stocks; spatial conflicts.

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INTRODUCTION

The fishery resources of the Adriatic Sea are under intense and increasing pressure from human activities, and the combined effects of fishing and habitat degradation have led to alarming reductions in many exploited fish stocks (Colloca et al. 2013, Russo et al. 2013, Scarcella et al. 2014, Vasilakopoulos et al. 2014). Demersal fish species are highly vulnerable to certain fishing activities (e.g., bottom otter trawling and *rapido* trawling; Pranovi et al. 2000), and all the assessed stocks are being fished above the fishing mortality levels leading to maximum sustainable yield (MSY; F_{MSY} ; STECF 2016). Concurrently, the Central and Northern Adriatic Sea (geographical sub-area [GSA] 17) has a wide continental shelf and eutrophic shallow waters, and demersal fish species are highly vulnerable to other anthropogenic impacts, such as the presence of contaminants and disruptions to the integrity of the sea floor (e.g., dredging for beach nourishment). Nearly all the fisheries management strategies currently adopted by Mediterranean countries are limited to the control of fishing capacity, fishing effort, and the application of technical measures, such as mesh size regulations, the establishment of minimum landing sizes, and closures of areas (e.g., towed gears have been permanently banned within 3 nautical miles [nm] of the coast) and seasons (e.g., towed gears are not used for fishing during the summer months; Scarcella et al. 2014). However, such technical measures have rarely been supported by scientific evidence (Leonart and Maynou 2003). Before implementing a reduction in fleet capacity that would probably lead to sustainable and optimal exploitation of demersal resources but also to a heavy negative socio-economic impact on local fishing industries, spatial management measures should be evaluated for appropriate application.

The spatial distribution of many marine populations is often a mosaic of habitat patches that are functionally connected at multidimensional levels (Nagelkerken et al. 2013). This type of ecological knowledge is becoming increasingly important to help achieve a sustainable exploitation of commercially important marine populations through the protection of essential fish habitats that play a key role for population processes such as spawning and recruitment. By

accounting for this bio-complexity, specific and alternative spatial management of trawling efforts could reduce the fishing mortality of juveniles. Therefore, the early concerns of the Food and Agriculture Organisation—General Fisheries Commission for the Mediterranean (FAO-GFCM) regarding fleet overcapacity and high fishing pressure in the inshore nursery areas, which might necessitate closures, have been priorities for discussion since the 1950s (Caddy 1993).

In the Adriatic Sea, where most of the harvested stocks are overexploited due to nonselective exploitation patterns and opportunistic fishery behaviors (Colloca et al. 2013, Russo et al. 2015, STECF 2016), the protection of the main nurseries of commercial species is increasingly viewed as a major step toward the achievement of more sustainable exploitation patterns. The recent landing obligation, introduced by the reform of the EU Common Fishery Policy, CFP (EC 2013a, b), is promoting the application of technical measures aimed at discouraging the capture of undersized specimens of commercial species in the Mediterranean Sea. These measures include the closure of areas where juveniles congregate at the end of their planktonic dispersal phase. The implemented management measures for the sustainable exploitation of fishery resources in the Mediterranean Sea (EC 2006) provide some guidelines for the habitat conservation in the Mediterranean Sea, with particular attention devoted to the protection of nursery areas. This regulation has the potential to yield important conservation benefits, and it is primarily based on two assumptions:

1. Juvenile fish are particularly vulnerable to a fine-mesh trawl fishery (Caddy 1993), especially when the fish are concentrated in nursery areas, and
2. a reduction in fishing mortality on immature fish represents a fundamental prerequisite for sustainable fisheries, which follow the “spawn at least once” rule (Beverton and Holt 1957).

In the present paper, we focus our effort on investigating a suite of alternative spatial plans for a more effective management by minimizing conflicts among fishing activities (trawlers vs. set netters) and by mitigating the population effects on four demersal stocks of high commercial

importance: common sole (*Solea solea*), hake (*Merluccius merluccius*), red mullet (*Mullus barbatus*), and spottail mantis shrimp (*Squilla mantis*). By applying a finely resolved modeling approach in space and time, we studied the effects of these alternative plans on the sustainability of the exploitation of these four fisheries species and the economic viability of the Italian catch sector to the fishery. Furthermore, we examined whether such plans are sufficient to mitigate the potential conflicts between different activities without affecting their relative profitability. We then incorporated the bio-complexity of the fish and fisheries taking place in the Adriatic Sea in interaction with some new spatial plans by modeling the structure of the harvested populations in both space and time, as well as in conjunction with the dynamics of the spatial distribution of the fishing effort for the different fishing methods operating at sea. We were able to provide some clear answers about whether the spatial plans are sufficient to ensure a sustainable and viable fishing in the area. We also investigated whether the displaced fishing effort impacts other benthic habitats when the fishery is constrained by the plans.

METHODS

The study area

The Adriatic Sea is an elongated basin located in the northern Mediterranean Sea, between the Italian Peninsula and the Balkans, with its major axis aligned in the northwest–southeast direction. The geo-morphological characteristics of the Adriatic Basin, geo-political changes along the eastern coast, existing national statistical divisions, and the fishery resource distribution have led to the identification of two GSA. Croatia, Bosnia-Herzegovina, Italy, and Slovenia border the GSA 17 (Northern and Central Adriatic Sea), and Albania, Italy (southeastern coast), Serbia and Montenegro are included in the GSA 18 (South Adriatic Sea; AdriaMed 2001). The GSA 17 has an extended continental shelf and eutrophic shallow waters; the southern part of the basin is characterized by the meso-Adriatic depressions (Pomo Pits), where the depth decreases approximately 270 m. Instead, a narrow continental shelf and a marked, steep continental slope characterize the Southern Adriatic (GSA 18). The

present study will focus on the GSA17, the most productive area of the Mediterranean Sea (Campanelli et al. 2011). In fact, the rivers flowing down along the western coast of this sub-basin contribute to approximately 20% of the whole Mediterranean river runoff (Hopkins 1992) and introduce large fluxes of nutrients (Cozzi and Gianì 2011). Due to the pronounced seasonal fluctuations in environmental forcing, coastal waters show a high seasonal variation in bottom temperature, ranging from 7°C (winter) to 27°C (summer). The thermal variability of the deeper areas is very much reduced, with values ranging between 10°C (winter) and 18°C (summer) at a depth of 50 m (Russo et al. 2012). This strongly influences the spatial distribution of the resources and, consequently, the local impact of the fishing activities. Despite these varying conditions, the Adriatic Sea, and GSA 17 in particular, is one of the most intensively fished area in Europe and the trawling hot spots show an intensive fishing pressure exceeding 10 times per year (Eigaard et al. 2016). This high widespread fishing pressure is given by the fact that the GSA 17 represents the largest and the best-defined area of occurrence of shared stocks in the Mediterranean Sea, and the fleet operating in this area includes all fleet segments, from small-scale fishery vessels to large trawlers. The demersal fishery takes place on the entire continental shelf and exploits a high number of species, characterizing the Adriatic fisheries (as well as the Mediterranean fisheries in general) as remarkably multi-specific. Catches are composed by mainly young individuals; in fact, the most representative age classes are age 0, 1, and 2 (Colloca et al. 2015). Most fishing activity is carried out by bottom otter trawlers and *rapido* trawlers, and the use of set gears (e.g., gillnets, trammel nets, and traps) is typically limited to the coastal areas (i.e., towed gears have been permanently banned within 3 nm of the coast) and/or areas unsuitable for trawling. This study was developed considering that only the Italian side of the GSA 17 and only the Italian fishing fleets were included in the model.

The agent-based modeling approach

The DISPLACE model framework (Bastardie et al. 2014, 2015) is developing a research- and advisory-based platform to transform fishermen's

detailed knowledge and micro-decision-making behavior into simulation and management evaluation tools. This involves advanced methods to assess and provide advice on the bio-economic consequences for the fisheries and fish stocks of different fishermen decisions and management options. DISPLACE is an agent-based simulation model developed to support maritime spatial planning and management issues, especially from the perspective of the fisheries. Agent-based models (Railsback and Grimm 2012) aim to consider the socioeconomic and ecological processes at the individual scale (e.g., the fishing vessels) to capture the effects of human decisions at that level and then go through the individual processes up to the aggregated dynamics (e.g., the fisheries as a whole or other marine ecosystem components). A particular strength of the agent-based approach is that it is an adequate level to model processes at the spatial (2×2 km) and the time scale (hourly time steps) closer to the spatial and time dynamics occurring in human decision-making and fish populations dynamics (Ulrich et al. 2012). It is also closer to the appropriate scale for dealing with management issues such as marine spatial planning (MSP; ADRIPLAN 2015). The agent-based approach is also keen on integrating process-based mechanistic relationships that give the advantage of being able to better predict in novel conditions (Stillman et al. 2015). Accordingly, DISPLACE should be able to incorporate the spatial and temporal details to obtain a necessary understanding of the integrated fisheries, behavioral and resource dynamics. We used DISPLACE version 0.9.4 (www.displace-project.org).

Fleet dynamics

We applied the model to capture the fishing fleet dynamics at the scale of the individual fishing vessel, with each vessel conducting one type of fishing activity with either a trawl or set net, while also distinguishing the *rapido* trawl from the more widespread otter bottom trawl. A *rapido* trawl is a towed gear introduced into use in the Adriatic Sea at the beginning of the 1970s to target scallops and flatfish. This gear consists of a box dredge (usually 3–4 m wide) rigged with teeth (5–7 cm long) along the lower leading edge and a net bag to collect the catch (Giovannardi et al. 1998). An inclined wooden board is fitted to the front of the metallic frame to act as a

spoiler and for attaching the gear, which is towed at a speed of 5–7 knots while in contact with the seabed. Usually, 2–4 *rapido* trawls are towed simultaneously by each vessel (Pranovi et al. 2000). In the Northern Adriatic, the *rapido* trawlers, along with the set netters, exploit mainly the common sole. Given that individual data are not available for the Italian fishery, average values for vessels using trawl or set nets in the GSA 17 were used, but were specific to each activity and were obtained from official harbor statistics (Appendix S1: Table S1). For larger vessels, the relative spatial fishing effort distributions per activity (Appendix S1: Figs. S2, S3) were obtained from the Italian vessel monitoring system (VMS), which is a satellite-based system held by all the fishing vessels with a length over all ≥ 12 m (EC No. 1224/2009). For the small-scale gillnet fishery, for which VMS data are not available, information on the fishing grounds was obtained from index suitability maps (Appendix S1: Fig. S4); these maps were defined by the relative likelihood of the fleet to visit the potential fishing grounds based on the suitability of these areas (according to bathymetry, distance to coast, etc.; Kavadas et al. 2015). This study was developed assuming that the considered fishing vessels land only in their home harbor (80 km for trawlers and 15 km for set netters), and each vessel distributed its effort within this range and per zone relative to the frequencies given by the relative effort data layer that was given as input at the initial stage. Fishing gear-specific selectivity ogives and fixed, stock-specific, spatial catch rates were applied per type of activity and vessels. Considering the differences among the body shape of the four species, selectivity was assumed to be species-specific (Fabi et al. 2002). The mesh sizes considered to define selectivity curves were 68 mm stretched for gillnets and 50 mm diamonds for otter and *rapido* trawlers, with these mesh dimensions being the most used in the GSA 17 (Appendix S1: Fig. S1). The Italian vessels considered in this study usually do not change gear during the year. However, exceptions were made by some gillnetters, who in some rare cases switched to bottom trawling; this modification never occurred during a trip. Each trawler vessel was assumed to work from Monday to Thursday, leaving the harbor each day at

4 a.m. and returning at 10 p.m., in agreement with the regulation that allows a vessel to spend a maximum of 72 h at sea per week (Regulation 03/07/2015). Therefore, the general observed trip pattern was reproduced in the model for the trawlers. In reality, the subdivision of time at sea per day might vary among harbors. Usually, gillnetters go fishing every day, but less frequently on the weekends, releasing their nets in the afternoon and pulling them in the morning of the following day. Thus, in the model, these vessels were considered to work 5 d/week, with an average daily fishing time of 12 h. In total, 596 “agent” vessels were simulated, comprising 315 set netters, 262 otter trawlers, and 19 *rapido* trawlers. For practical reasons, such as to speed up the simulations and reduce the overall size of output, we assumed that each agent represented four vessels. These groups of vessels were defined as “super-individuals.” The specifications for each agent, which included the individual catch rates, hourly fuel consumption rate (deduced from the vessel engine power), fuel tank capacity, and fish storage capacity, were therefore multiplied by four to obtain values for each of the “super-individuals.”

Stock dynamics

We designed the model to handle the spatial population dynamics of four important commercial species in the area: hake (*Merluccius merluccius*), common sole (*Solea solea*), red mullet (*Mullus barbatus*), and the spottail mantis shrimp (*Squilla mantis*). These species account for approximately 40%, 30%, and 50% of the landed value for the trawlers, gillnetters, and *rapido* trawlers, respectively; furthermore, these species have been assessed by the FAO-GFCM management and STECF for estimating the stock levels (STECF 2013, 2016). Norway lobster (*Nephrops norvegicus*) is also of great commercial interest for demersal fisheries in the area but we did not account for this stock because there are different sources of uncertainty around this stock and there is no official stock assessment (STECF 2016). The fish body size-population structure (using total length for fish) was discretized into 3-cm bins for all species (3 mm carapace length for spottail mantis shrimp); growth parameters were the same used in the last stock assessments developed for these species (Appendix S1: Table S2), stock

assessments from which population estimates are derived (Appendix S1: Table S3). The population spatial distributions were obtained from data collected during scientific surveys. In particular, the MEDITS survey program (an international bottom trawl survey in the Mediterranean, Anon 1998) intends to produce basic information on benthic and demersal species in terms of the population distribution, as well as the demographic structure, through systematic bottom trawl surveys of the continental shelves and the upper slopes at a global scale in the Mediterranean Sea (Bertrand et al. 2002). In the GSA 17, this survey program is being conducted by the Laboratory of Marine Biology and Fishery of Fano (Italy) in cooperation with the Institute of Oceanography and Fisheries of Split (IOF, Croatia) and the Fisheries Research Institute of Slovenia (FRIS, Slovenia).

The SoleMon survey is being conducted by the National Research Council (CNR-ISMAR, Italy) in cooperation with the National Institute for Environmental Protection and Research (ISPRA, Italy), the IOF (Croatia), and the FRIS (Slovenia) using *rapido* trawls (width = 3.69 m, weight = 200 kg, and codend stretched mesh size = 40 mm; Grati et al. 2013).

By applying geostatistics to the survey data, interpolated levels of stock abundance can be obtained by the categories of fish sizes (Appendix S1: Figs. S5–S8). For each species, the spatial distribution was described according to three size groups on the basis of commercial categories (small, medium, and large individuals) to accommodate the variation along the growth of the individuals relative to where they locate themselves in the marine environment during the life cycle: hake: 0–20 cm Total Length (TL), 20–25 cm TL, and >25 cm TL; common sole: 0–20 cm TL, 20–25 cm TL, and >25 cm TL; red mullet: 0–9 cm TL, 9–12 cm TL, and >12 cm TL; and spottail mantis shrimp: 0–26 mm Carapace Length (CL), 26–31 mm CL, and >31 mm CL. The spatial distribution of the species (variable: kg/km²) was estimated by means of Ordinary Kriging, a geostatistical method of interpolation, which is the procedure for predicting the value of attributes at unsampled sites from measurements made at point locations within the same area or region. In Ordinary Kriging, the spatial variation of the data is described by a variogram, a mathematical function that expresses the semi-variance between

points as a function of distance between the observation points (Burrough and McDonnell 1998).

Intertwined stock and fleet dynamics

The harvest (in kilos) from each active vessel at sea in DISPLACE depletes the underlying stocks, as the individual catch rates are specific to the species and affect the size structures of the population according to the varying selectivity for body size of the fishing vessel gear. This size-structured depletion dynamically links back to the underlying population models as detailed in Bastardie et al.'s (2016: appendix A). Contrary to Bastardie et al. (2016), the catch rates were not assumed to depend on the available biomass by locality (unless the catch is greater than the total available biomass). Therefore, the difference in the amount and price of the catch from a vessel or from one trip to the next mainly arises from the varying duration of the fishing event, the specific selectivity of the various gears being used, and the variation in the mixture of species and abundance per size on the localities where the vessel is fishing. Hence, an assumption is made of hyperstability in catch rates (e.g., Harley et al. 2001) that are in agreement with the best data because we do not have data on spatial catch rates that will allow us to index catch rates according to the various levels of stock abundance. *Rapido* and otter trawlers are assumed to target the four species, whereas the set netters are assumed to target common sole and spottail mantis shrimp, as the hake is very rare in the set netters' fishing grounds and the red mullet is not retained by the mesh sizes used in gillnets. After each trip, simulated fishing vessels return to port and earn money from the landings in harbor where the fish prices were informed per marketable category (Appendix S1: Table S4). These fish prices were assumed not depending on the demand conditions for seafood. In an additional step, the revenue from the landings from the previous trip was determined using the amount of the catch represented by species other than the four studied species in the total revenue (revenue times 2.5, 3.3, and 2 for the otter trawlers, gillnetters, and *rapido* trawlers, respectively). For each vessel, the probability of visiting a certain fishing ground is updated over time from information obtained at the end of each trip concerning the expected profit the vessel could make on each

ground and the expected profit according to the catch rates during this last trip. Finally, estimated depletions in the stock numbers in each of the localities, obtained mainly from other countries active in the Northern Adriatic and other catches from Croatia and Slovenia (in 2014, hake: 2348 tons; common sole: 136 tons; red mullet: 1712 tons; mantis shrimp: 0 tons; STECF 2016), were applied evenly over the spatial distribution of the stocks inside their respective exclusive economic zones.

Benthic habitats

Benthic habitats were described according to the information included in Santelli et al. (*In press*; Fig. 1), who analyzed the megazoobenthic fauna collected during the SoleMon survey and clustered the samples in four different ecological associations. The different stations were then interpolated to obtain a picture of the study area at the scale of the Central and Northern Adriatic. Group A was dominated by *Holothuria (Panningothuria) forskali*, followed by *Amathia semiconvoluta*, *Parastichopus regalis*, *Phallusia mammillata*, and *Holothuria tubulosa*. Group B included *Ocnus planci*, *Astropecten irregularis*, and *Suberites domuncula*. Group C included three main species: *As. irregularis*, *Anadara kagoshimensis*, and *Anadara transversa*. Group D was dominated by *Lio-carcinus depurator*, followed by *As. irregularis*.

The presence of the group A (i.e., combinations A000, AB00, ABC0, ABCD, A0C0, A0CD, and A00D; Fig. 1) is an object of focus because it includes holothurians, which exhibit evisceration if subjected to physical or chemical stress; this evisceration causes problems to fisheries because this event makes the fish less suitable for marketing ("yellow fish" problem). This behavior, together with the high presence of the bryozoan *Am. semiconvoluta*, which obstructs the nets and compromises their efficiency, discourages fishing in this area, which is actively avoided by trawling activities. Thus, gillnetters represent the only gear fishing in these grounds and catch many sole, skates, and other large fish.

Management and population scenarios

According to the EC (2013b), stocks should be fished at F_{MSY} levels, that is, the level of fishing mortality (F) that allows the achievement of the MSY (e.g., some harvest control rules are based

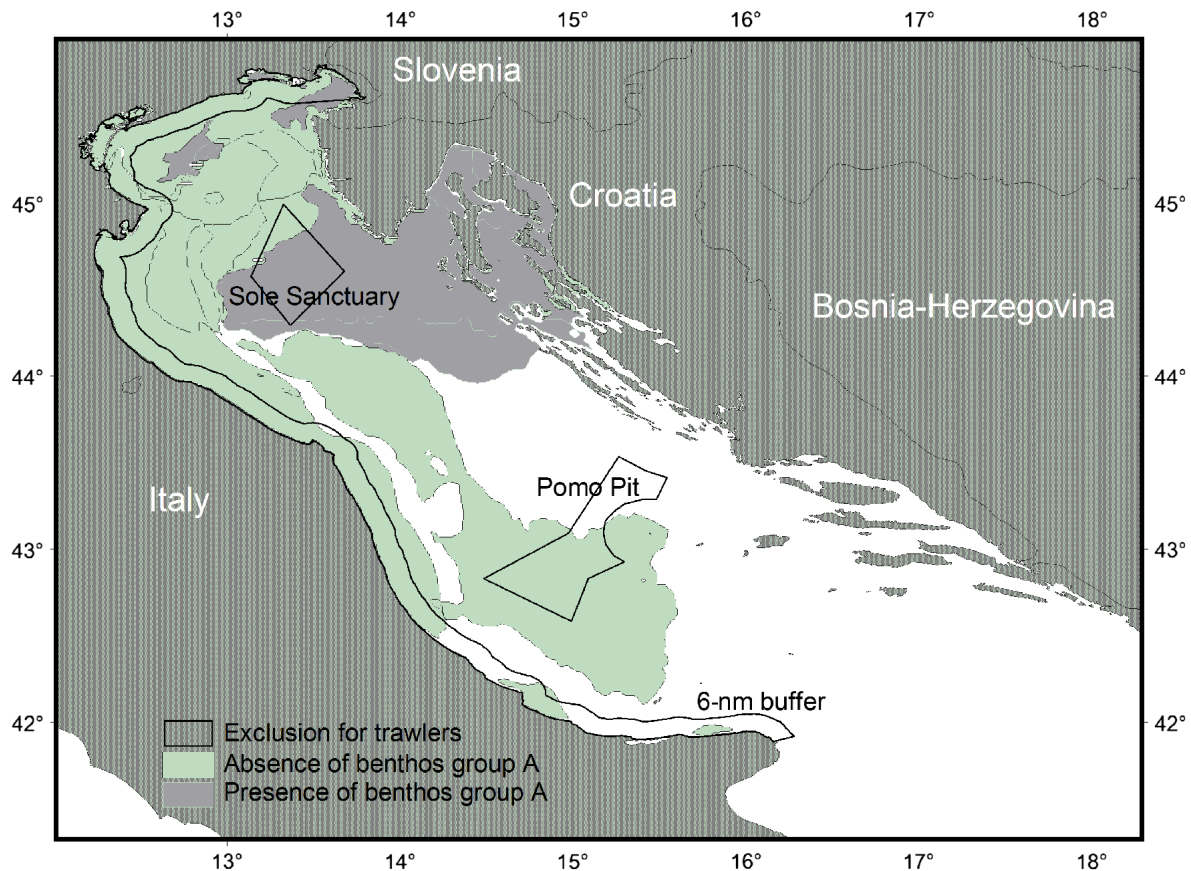


Fig. 1. Benthic communities in Northern Adriatic Sea defined as grain-size map with persistence of the Holothurian-dominant group (group A) analyzed in Santelli et al. (*in press*) with colored polygons coded in presence/absence for this group. The black solid line polygons give some of the tested exclusion for trawlers, that is, 6-nm buffer, sole sanctuary polygon and Pomo Pit ban.

on the deployed effort at sea that could match the intended F_{MSY}); DISPLACE is able to calculate the F value as an emergent property, but values were not considered for management purposes but were used to describe the status of the stocks instead. The aim of this study was to test alternative spatial management scenarios for reaching an effective spatial management within the Northern and Central Adriatic Sea, minimizing conflicts among fishing activities (large trawlers and small-scale fishers) and mitigating the effects for the four species (hake, common sole, red mullet, and mantis shrimp) considered in this study. This objective was reached by projecting DISPLACE for the next 5 yr with the purpose of evaluating the benefits that would arise in the case of modifications of fishing grounds. In

particular, the costs sustained to reach more distant fishing grounds were taken into account, with evaluations of these additional costs being compensated by the economic value of the new catches. This allowed the effects of the spatial management scenarios on the four considered stocks to also be analyzed.

The spatial management scenarios tested in this study take into account the management regulations active in the Italian waters. In particular, the Italian regulation foresees (1) a ban for trawlers inside the 3 nm from the coast and (2) a temporary closure of the Pomo Pit area for bottom trawlers effective from 26 July 2015 to 26 July 2016 (D.M. 3/07/2015). Considering these measures, set gears are used almost exclusively inside the 3-nm strip, avoiding conflicts with

active/mobile gears outside this limit. This situation suggests two possible future scenarios (4- or 6-nm trawling ban) that suppose a reduction in the fishing ground for trawlers and a potential increase in the fishing ground of gillnetters. The closure of the Pomo Pit highlights the importance of reducing the fishing pressure on vulnerable areas (e.g., spawning and nursery areas) that are considered of biological interests for commercial species, as also emphasized by AdriaMed (2008), De Juan and Leonart (2010), and Mediterranean Sensitive Habitats (2013).

Considering this information, the following scenarios were tested (Fig. 2):

1. +excludeInBuffer4nm—trawling ban within 4 nm from the Italian GSA17 coast
2. +excludeInBuffer6nm—trawling ban within 6 nm from the Italian GSA17 coast
3. +excludeInPomoPitBan—trawling ban within Pomo Pit (already closed from 26/07/2015 to 26/07/2016; regulation established on 03/07/2015)
4. +excludeInSoleSanctuary—trawling ban inside the “sole sanctuary” (spawning grounds)
5. +excludeIn6nmSoleSanctuaryAndPomoPit—a combination of all the closures implemented at the same time
6. +excludeInBuffer6nmAndDispersion—evaluating the effect of the ability of the population to disperse and the potential effect from some fish to becoming accessible to the fishery. This scenario assumes the redistribution of the population over its homerange size every month instead of every quarter by default.

We obtained a quantification of the changes provoked by the implementation of alternative plans by running Monte Carlo simulations that projected the scenarios with varying spatial harvest patterns (from the activity of individual vessels), comparing them against the baseline situation where the current management was applied. A total of 50 stochastic runs were conducted per scenario and provide quantified changes to the activity-specific impacts on the economic return, on the sustainability of the harvesting strategies for the species considered in this study, and on the fraction of underlying sea-floor habitats enduring the fishing pressure.

RESULTS

The spatial distribution of the trawling fishing effort (Fig. 2) is in line with the one observed by Santelli et al. (*In press*), shaped to remain outside the Croatian national waters and also showing the avoidance of the grounds with presence of Holothurians and *Amathia semiconvoluta*. At this stage, no method exists to validate the spatial effort allocation from the set netters, but the error of placement is assumed to be low given their low mobility (<15 km from their home harbors).

The spatial plans have affected the baseline fishing effort allocation (Fig. 2). Hence, for the 4-nm buffer scenario, which excludes any trawling along the coast, and even more so for the 6-nm buffer scenario, a general drop in effort near the shore occurred to the detriment of more remote areas, whereas the increases in effort also concentrated along the border of the buffer areas. The effort is clearly removed from within the buffer areas (but not everywhere, as some netters could have increased their effort in some places), whereas a net increase along the border limits was measured. Closing the sole sanctuary (+excludeInSoleSanctuary) affected the effort allocation only in the vicinity of the closure because the total effort in the initial area was initially low. The effect of the Pomo Pit ban (+excludeInPomoPitBan) was much larger and resulted in the effort being redirected toward the surrounding areas but also toward some more remote areas when vessels searched for other opportunities far from the closed areas. Applying all the closures at once (+excludeIn6nmSoleSanctuaryAndPomoPit) largely changed the relative spatial allocation of the effort compared to the baseline, especially in the most northern and southern areas.

Overall, the change in the total fishing effort and the distribution effort in space from the coastal 4-nm buffer zone has not impacted the trawler revenue, whereas in contrast, exclusion from the 6-nm buffer area led the otter trawlers earning 15% less (Fig. 3) from lowered catches of the spottail mantis shrimp and common sole, as well as the *rapido* trawls earning 10% less (Fig. 4) from losses of common sole, red mullet, and spottail mantis shrimp species but gaining on hake. For trawlers, this loss is mainly explained by a smaller fraction of the time dedicated to actual fishing over the total incompressible trip

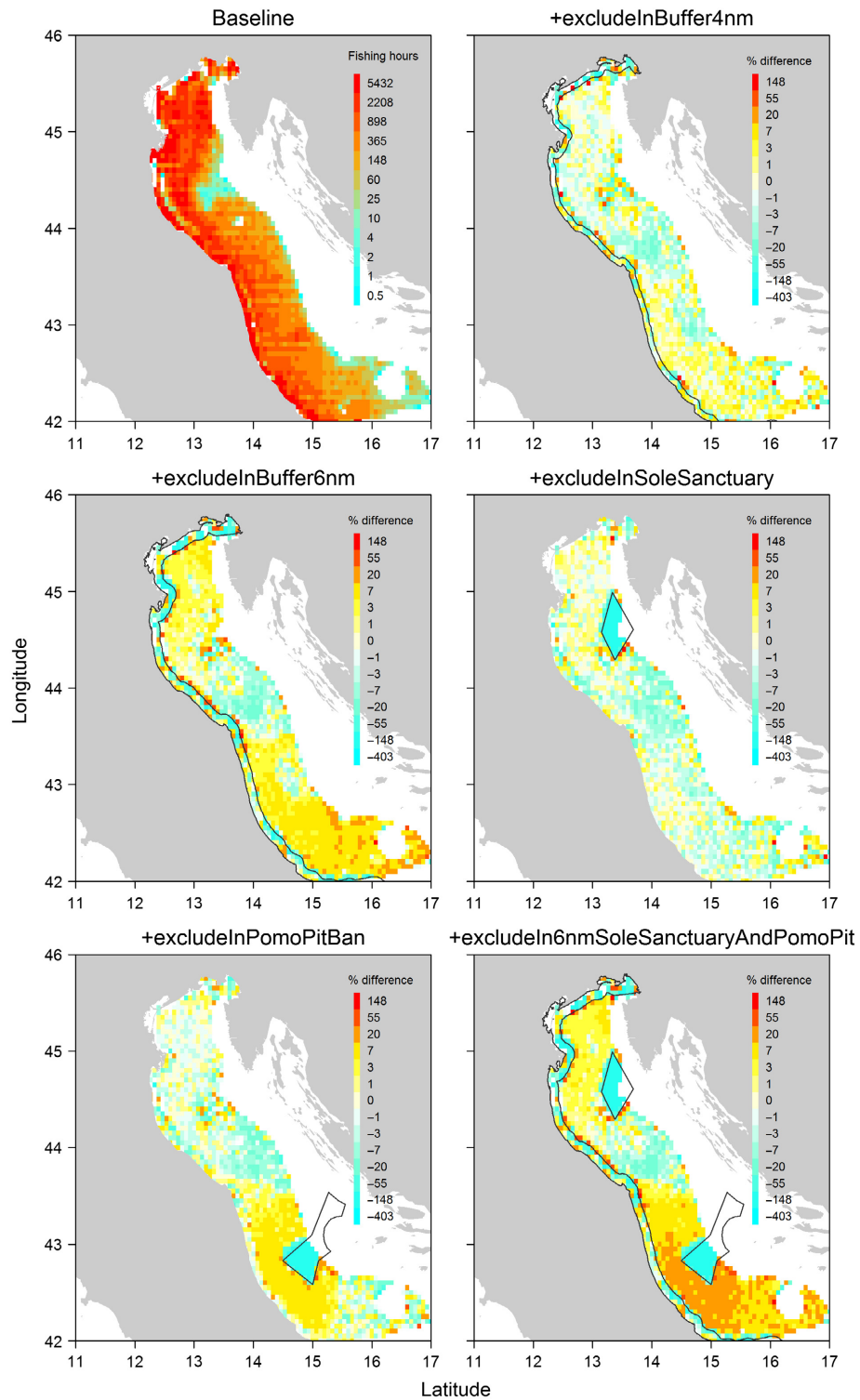


Fig. 2. Baseline spatial distribution of the Italian fishing effort and the percentage of relative change (per grid cell of 50 km²) per scenario. Fishing efforts are given as the accumulated tons over the five-year simulation horizon averaged over the 50 replicates per scenario.

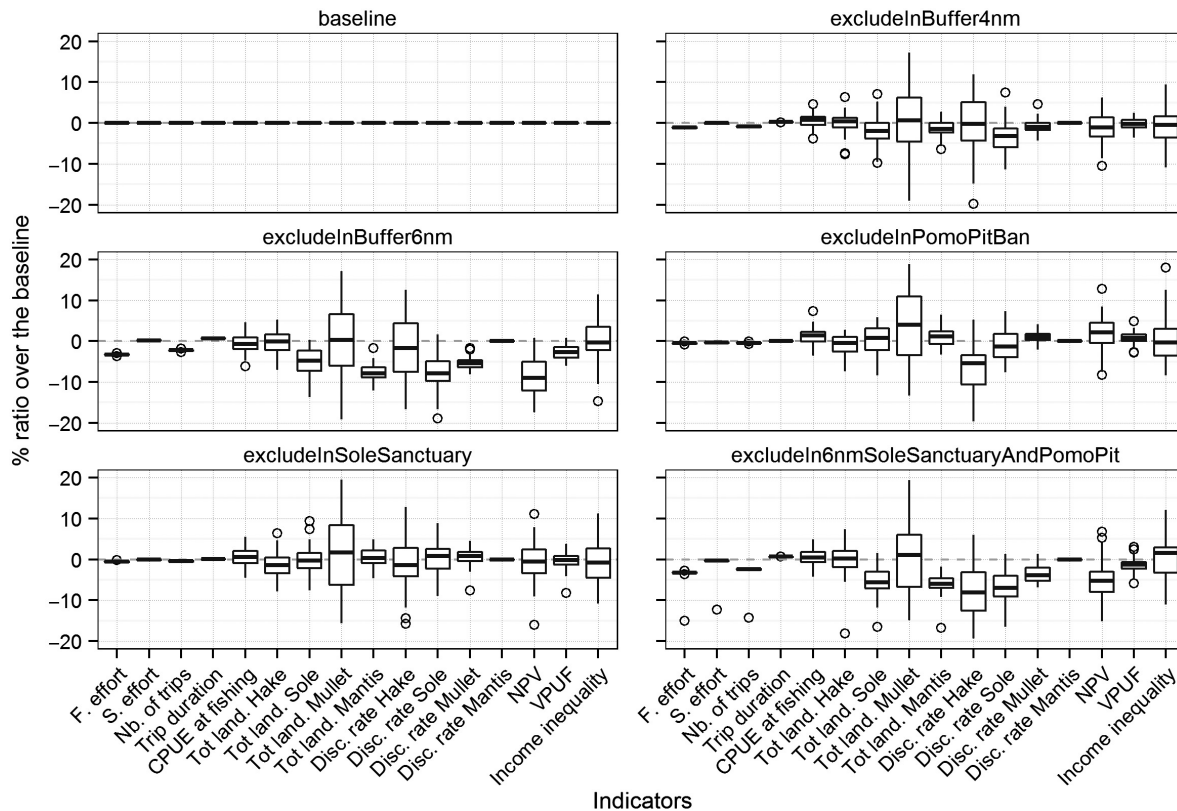


Fig. 3. Comparison of aggregated scenario outcomes (50 stochastic replicates per scenario) on the vessel performance indicators (percent relative to the baseline) for otter trawl vessels involved in the Italian coastal fisheries. The percentages are relative to the baseline condition for fishing effort (F. effort), steaming efforts (S. effort), number of trips (Nb. of trips), trip duration, catch per unit effort (CPUE at fishing), total landings for each considered stock (Tot land. species), discard rates for each species (Disc. rate species), net present value (NPV) with a 4% annual discount rate on GVA, value per unit fuel (VPUF), and income inequality computed based on the Hoover Index. The baseline is given by the “focus on high profit grounds” scenario, including the GoFishing and stopFishing decision trees designed to imitate the Italian daily trip pattern.

duration (up to -4% for the 6-nm exclusion for the otter trawl) because the fishing grounds are now farther from the departure harbors and the fuel used has increased (the engine consumes more during steaming phase). Concerning the more remote closure, the sole sanctuary has not significantly affected the net present value (NPV) for trawlers (Fig. 3) and also did not affect any other indicators, while the Pomo Pit ban has actually increased the revenue by 3% on average (Fig. 3) for otter trawlers fishing around the area (*rapido* trawl are not active in this area). Otter trawlers benefitted from the exclusion from the Pomo Pit area by experiencing a slight increase in their catch rate for red mullet (Fig. 3). Hence,

all combined exclusions showed that changes in the trawl trip pattern and the profitability are mostly driven by the 6-nm buffer zone, and a cumulative effect, rather than a multiplicative, synergic effect, is therefore detected.

The set netters benefited from the exclusion of trawlers at 4 and 6 nm (up to $+5\%$ in the NPV; Fig. 5). Because the netters spent the same amount of time at sea in any cases, the gain in revenue is due to the better efficiency gained from the higher catch rates (Fig. 5). This gain for netters was due to the greater amount of common sole and red mullet landed and also likely reflected catches with larger fish that are priced more. By contrast, no strong effect was detected

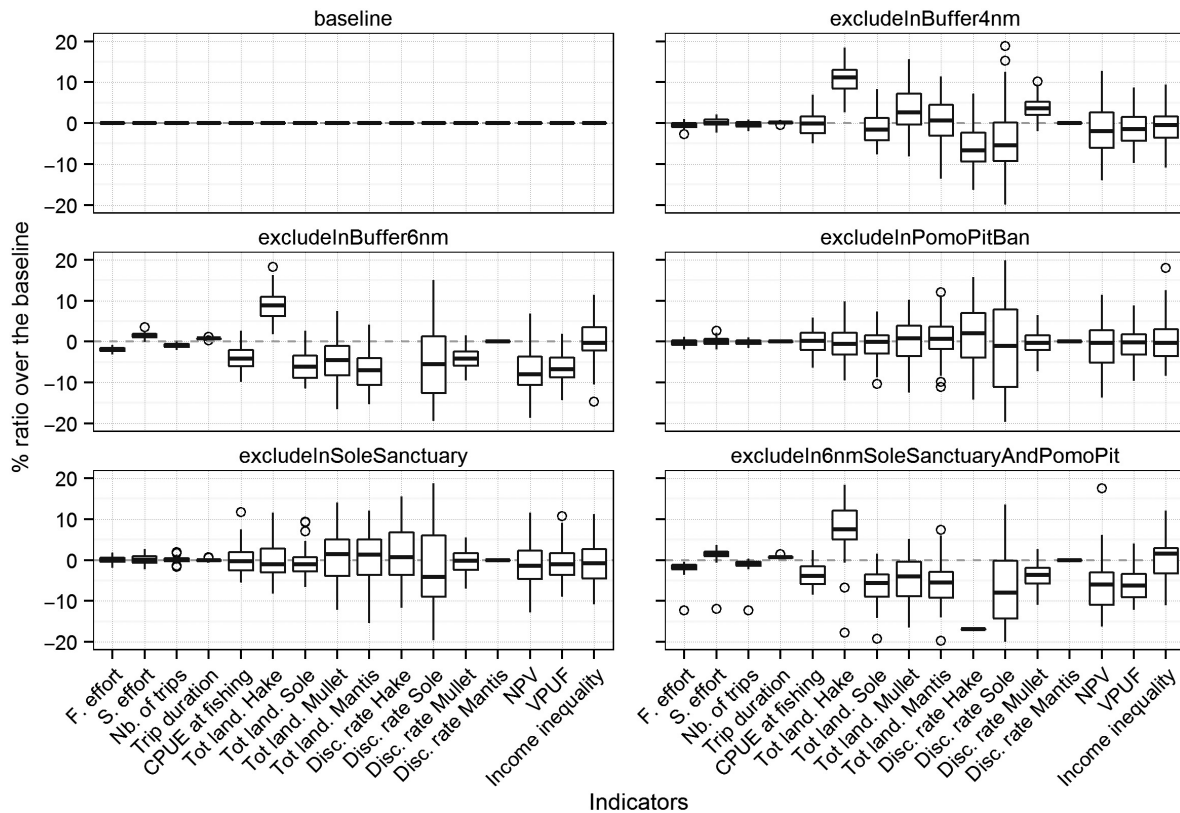


Fig. 4. Same as Fig. 3, but for *rapido* trawl.

on the set netters from the exclusion of trawlers from the more remote places such as the sole sanctuary and the Pomo Pit, in which fishing was banned, apart from higher red mullet landings and slightly less discard of common sole (Fig. 5) from better stock status on both stocks.

The various spatial plans influenced the amount of catches and their spatial extent, determining also a different depletion of the stock structure. By fishing for the fish of different sizes in the populations, the change in trawl effort allocation has come along with higher catch rates for set netters and with a large decrease in the discard rate for common sole regardless of the fishing activity. Both otter trawlers and *rapido* trawlers also show lower discards for hake, common sole, and red mullet (Figs. 4, 5) when excluded from the more coastal areas. These varying catch origins led to different impacts and depleted the underlying stock structures differently when the plans are in force. The buffer scenario led to displacement of the catches from outside the exclusion zones for

hake (Fig. 6) and red mullet (Fig. 7) not caught by set netters. However, slightly more common sole (Fig. 8) and mantis shrimp (Fig. 9) were caught from the coastal areas because the netters were allowed to fish there and increased the amount caught in this strip in replacement of the catches from the trawlers. This resulted in higher overall stock levels (in terms of the spawning stock biomass [SSB]; Fig. 10) for the four species from the implementation of the exclusion zones, and a slightly lower *F* for all stocks compared to baseline (Fig. 10). Even for the baseline scenario, the stock of common sole showed a declining trend in the SSB and did not appear to be sustainably exploited. In addition, the simulations showed that a large sensitive parameter accounted for this ability for the population to disperse, whereas a higher dispersion provoked a marked higher and more uncertain fishing mortality (*F*; Fig. 10), especially for the coastal common sole stock where the older sole were also slowly disappearing from the simulated populations, in contrast to the other

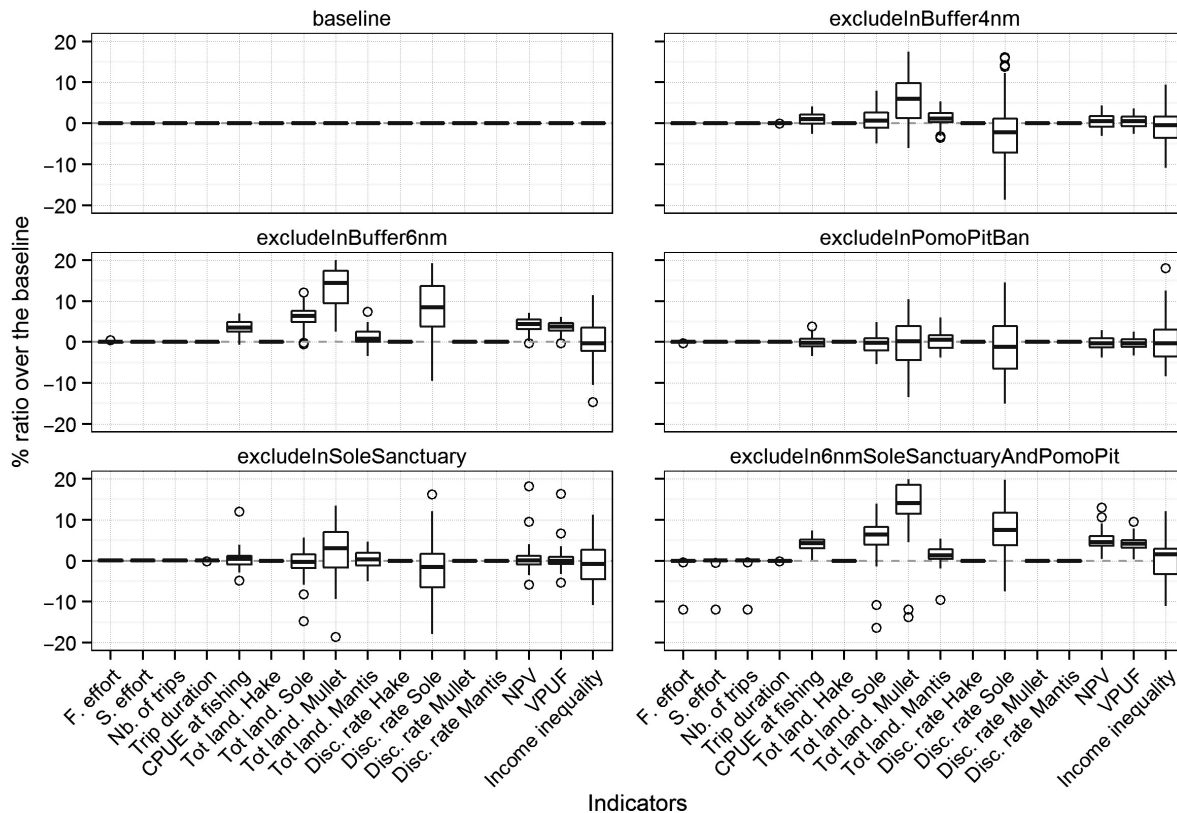


Fig. 5. Same as Fig. 3, but for gillnetters.

stocks. Under a high dispersion ability assumption, the common sole stock appeared more accessible for fishing by the set netters (Fig. 10), and along these trends, the trend for landings of, and therefore profits from, the sole is slowing over the five-year horizon (Fig. 10), and the tested exclusion scenarios were not able to correct for this (Fig. 10).

Not every vessel was impacted the same way, but when trawlers were considered at the individual scale (Fig. 11), the most negatively impacted vessels were also reported at the overall scale (e.g., Fig. 3). In contrast, according to the average outcome, set netters are, in general, better off for the gross value added to the baseline when individual results are observed, and only few of these set netters suffered very small losses when the buffer scenarios were implemented. None of these exclusion scenarios showed a large decrease in the energy efficiency (value per unit fuel; Fig. 11, right panel) relative to the baseline scenario but showed an increase instead, mostly from more efficient netters. When outcomes were viewed at the levels of

the communities/harbors (Appendix S1: Fig. S9), the harbor communities analysis made some disparities apparent when the different communities faced different impacts from the relative distribution of the stocks, fishing activity, fishing power, and harbor-specific prices for different type of fish. Consequently, some ports are largely affected by the buffer zone spatial plans, whereas ports in the Central Adriatic appear less affected. If it is expected that in narrow space, technical interactions between activities and population areas are likely affecting the port communities in various ways from some crowding/congesting effects (Fig. 12). For example, more vessels visit a narrower area, thereby generating less profitable trips, and the dominant effect comes from the loss experienced by the *rapido* and otter trawl fleet based in northern region.

The change in the benthic habitat trawled does not create potential adverse effects from the displacement of the effort on benthic communities, although this change can create problems to trawling activities (% difference on A000, AB00,

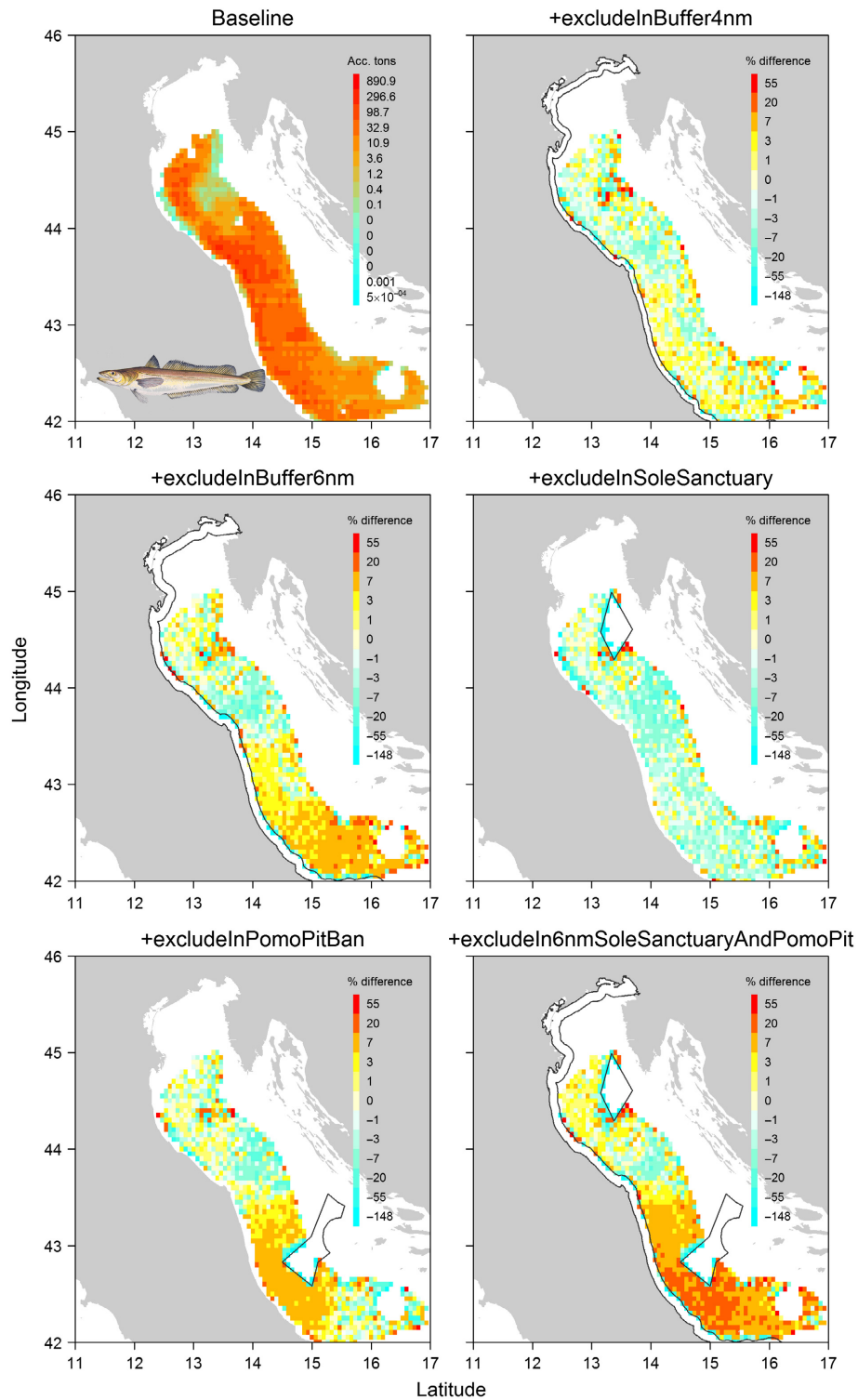


Fig. 6. Baseline spatial distribution of the Italian catches of the hake stock and the percentage of relative change (per grid cell of $\sim 30 \text{ km}^2$) per scenario. Catches are given as the accumulated tons over the five-year simulation horizon averaged over the 50 replicates per scenario.

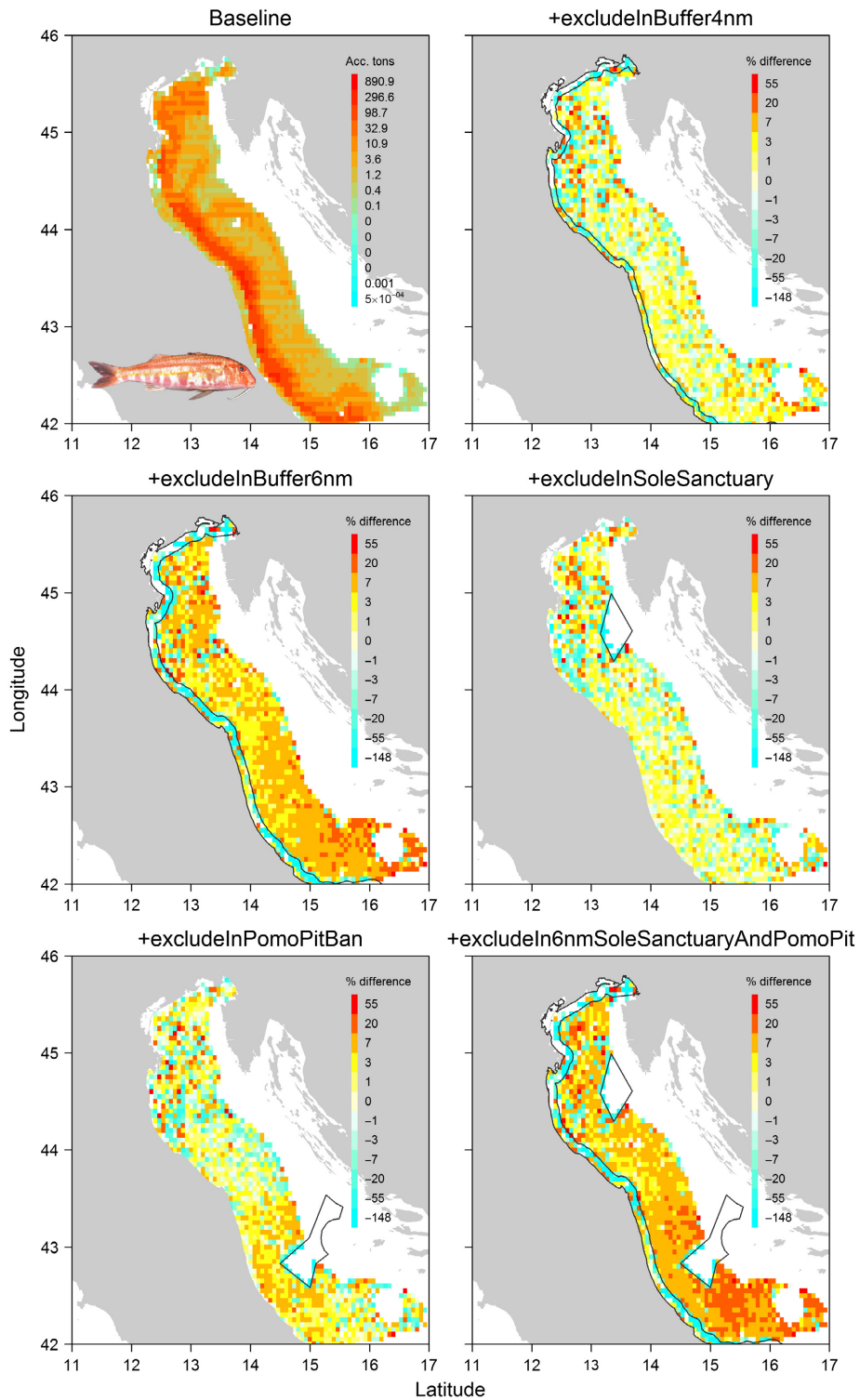


Fig. 7. Baseline spatial distribution of the Italian catches of the red mullet stock and the percentage of relative change (per grid cell of $\sim 30 \text{ km}^2$) per scenario. Catches are given as the accumulated tons over the five-year simulation horizon averaged over the 50 replicates per scenario.

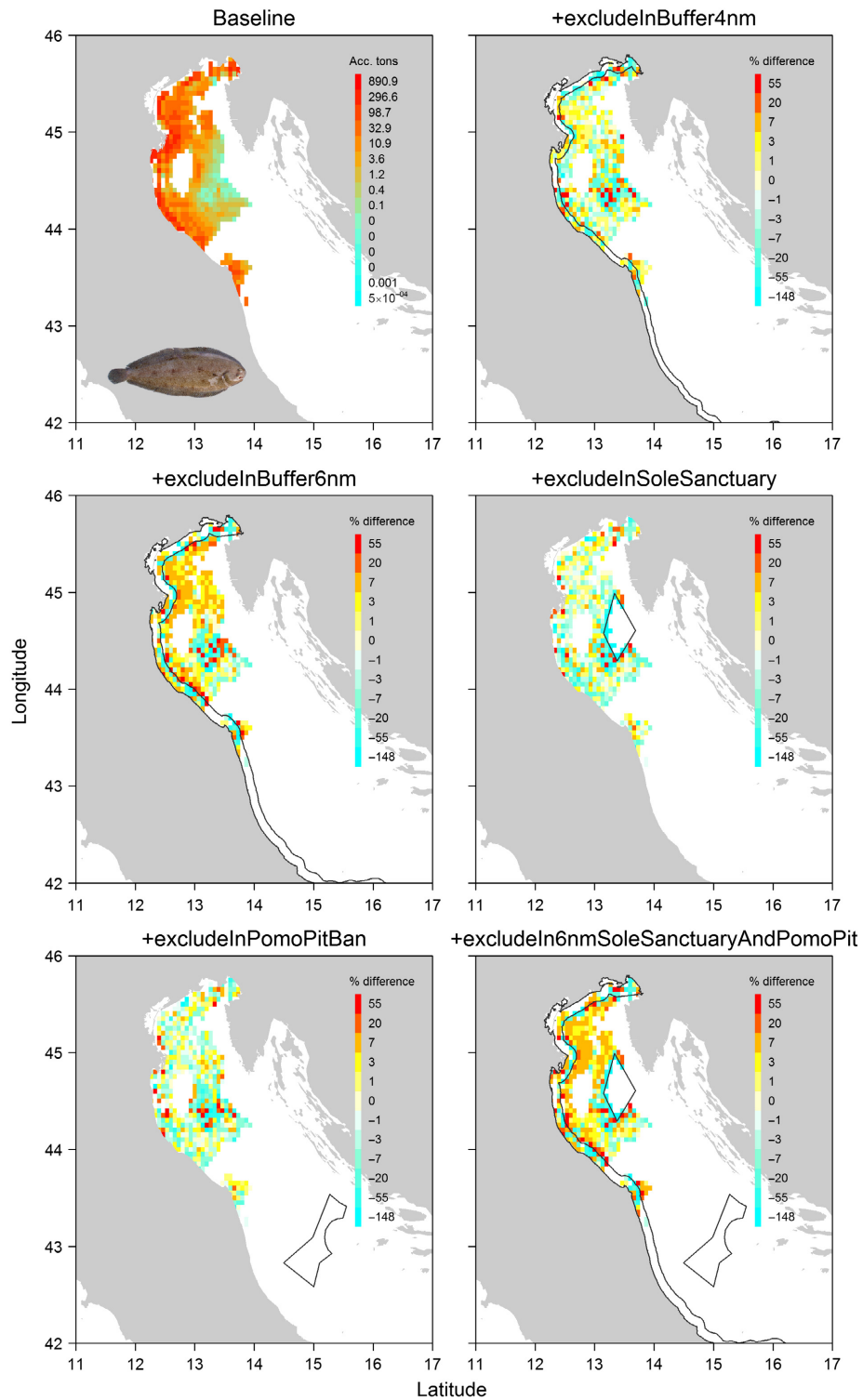


Fig. 8. Baseline spatial distribution of the Italian catches of the common sole stock and the percentage of relative change (per grid cell of $\sim 30 \text{ km}^2$) per scenario. Catches are given as the accumulated tons over the five-year simulation horizon averaged over the 50 replicates per scenario.

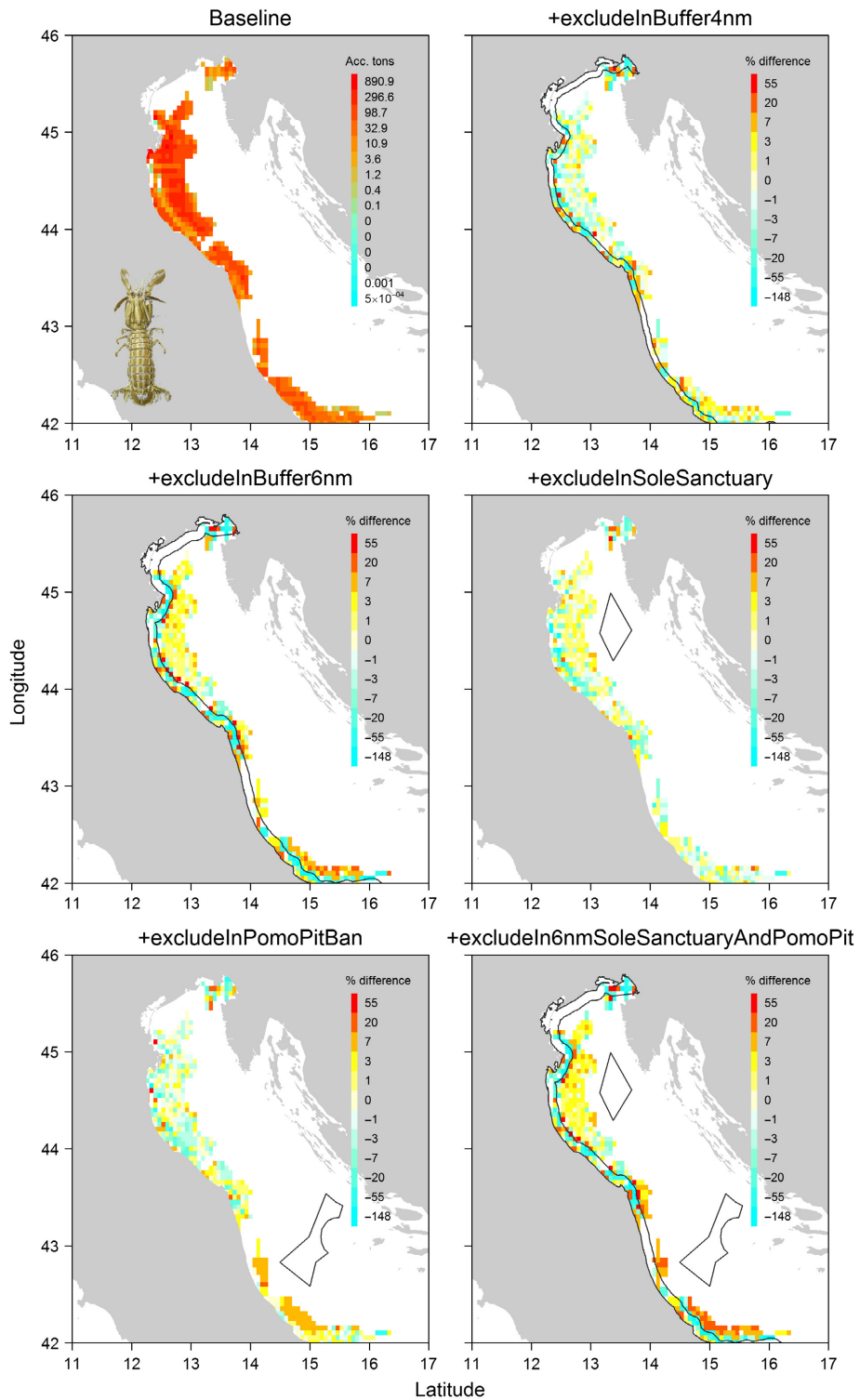


Fig. 9. Baseline spatial distribution of the Italian catches of the mantis shrimp stock and the percentage of relative change (per grid cell of ~30 km²) per scenario. Catches are given as the accumulated tons over the five-year simulation horizon averaged over the 50 replicates per scenario.

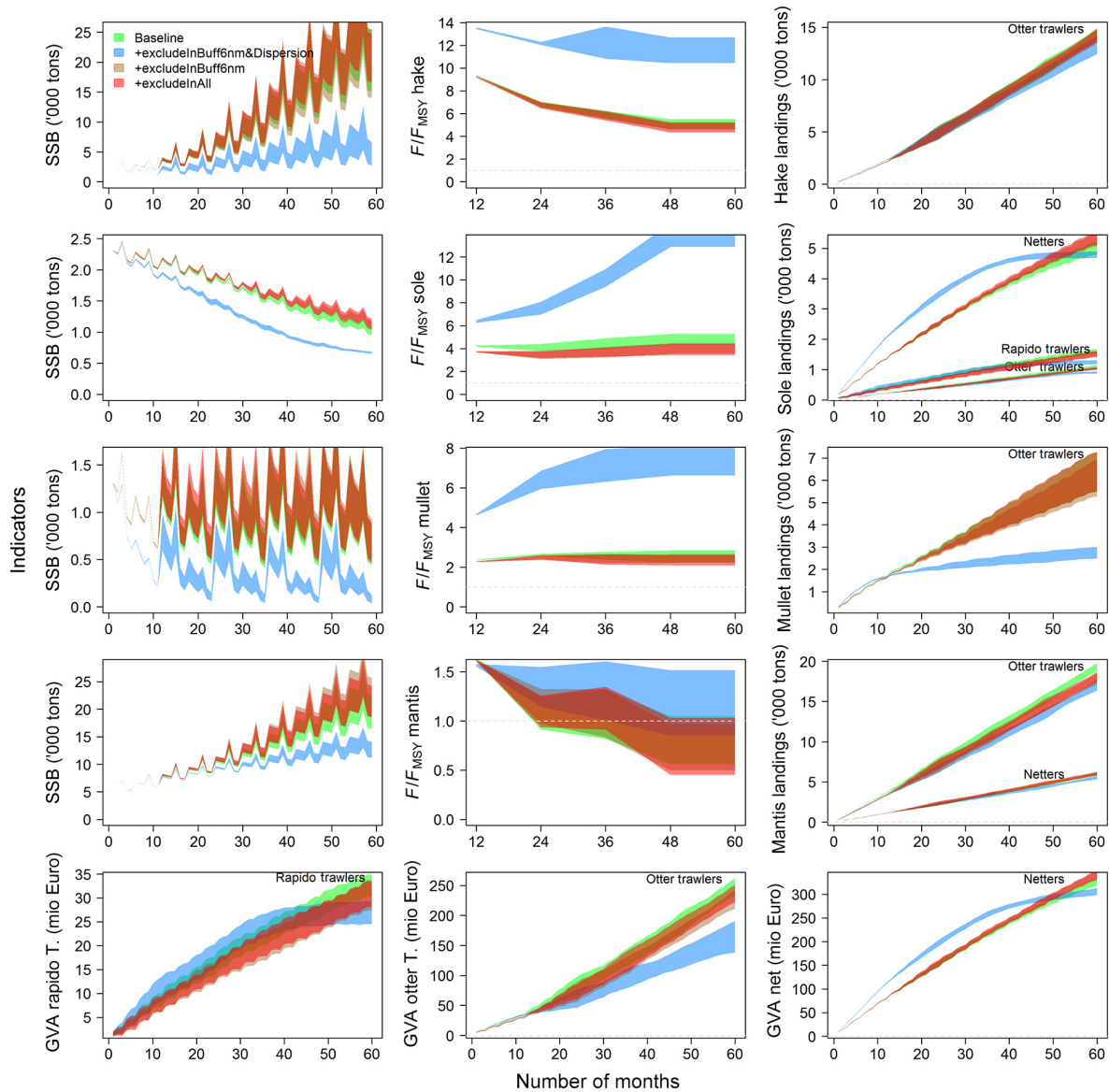


Fig. 10. Spawning stock biomass (SSB); accumulated landings; ratio of fishing mortality over the F_{MSY} reference (F/F_{MSY}) for hake, common sole, mullet, and mantis shrimp; and accumulated revenue (GVA) per fishing activity (*rapido* trawl, otter trawl, and netters) per month over the simulation period up to the horizon time (month 60 in 2019) when focusing on the Italian coastal fisheries (50 stochastic replicates per scenario).

ABC0, and ABCD Holothurian-dominant habitats) given the small general decrease in the total fishing effort (Table 1). The findings, therefore, do not show any net effort displacement toward this habitat type, which could have been unrealistic because of the difficulty of fishing in this habitat with the current technologies available. However, the 6-nm buffer and the sole sanctuary

scenarios indicate that a net gain in catch rate for mullet, but not for common sole, is probable in the Holothurian habitats. Such a change indicates that some fishermen changed their effort pattern, thereby avoiding fishing on this habitat type, mainly because of the closures that occurred in this habitat.

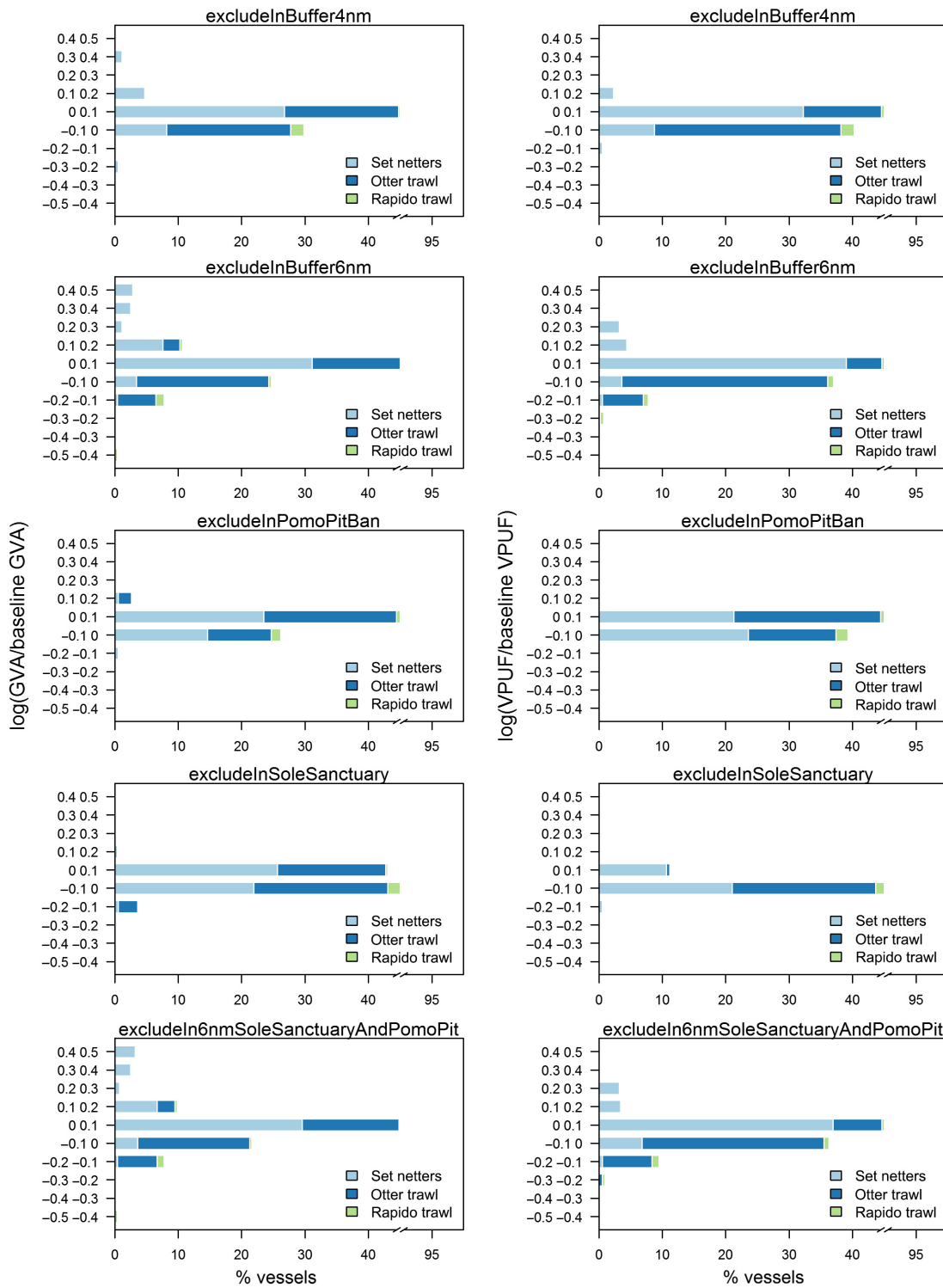


Fig. 11. Percent of vessels binned per categories (left: gross value added [GVA]; right: value per unit fuel [VPUF]) per scenario relative to the baseline situation (0 means no difference with the baseline) for the three different activities (net setters, otter trawl, and *rapido* trawl).

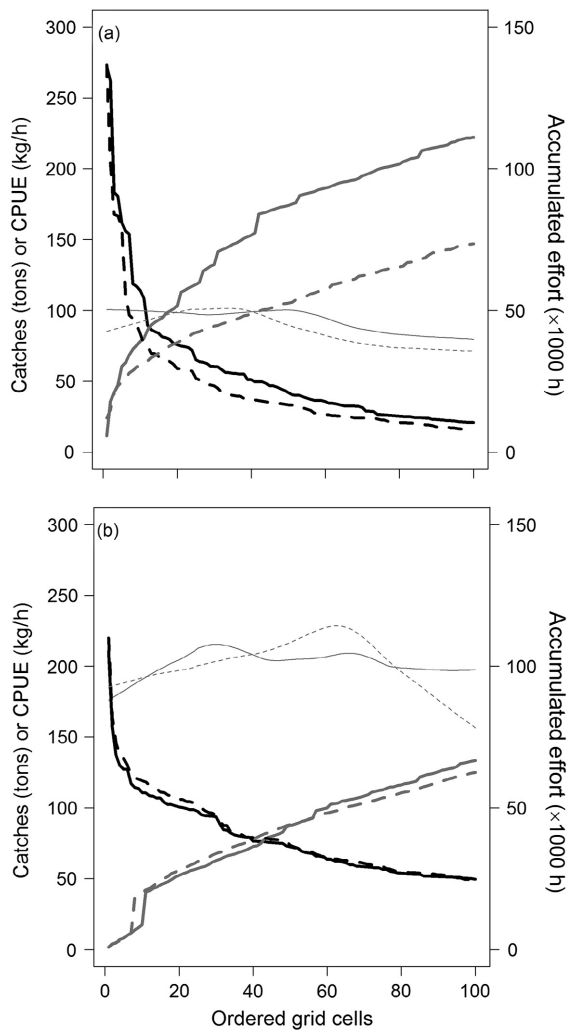


Fig. 12. Accumulated landings at the horizon time (black curve), accumulated fishing effort (gray curve), and smoothed catch rates (gray thin curve) in each grid cell of geographical sub-area 17 for the baseline scenario (solid lines) and the full spatial plans (dashed lines) averaged over the 50 replicates per scenario. Grid cells are ordered from the highest to the lowest catches. Only the top 100 grid cells are kept on each graph: (a) for cells with latitude greater than 45.5° N and (b) for cells with latitude lesser than 45.5° N.

DISCUSSION

Early identification of impact and opportunities for multiple use of space in the EU waters (EC 2013a) calls for in-depth analyses of the trade-offs in the allocation of space in the different

socioeconomic sectors and the damage caused to marine habitats and the integrity of the seafloor by the different practices. In a fisheries context, management should ensure that the fishing activities are occurring in a sustainable manner—fishing without running the risk of not having enough left for the long-term exploitation of the commercial stocks—and that the plans are also built in accordance with the protection of the marine ecosystems and fisheries (EC 2013b). By a greater understanding on how the spatial fishing effort could redistribute in space, we contributed to assess the effect of the various spatial plans on the mitigation of conflicts among the different fishing activities (trawlers vs. set netters) and evaluated whether this change would make exploitation sustainable across the following five dimensions: (1) maintaining the accessibility of the fishing grounds still reachable at reasonable costs, (2) ensuring stable yields from the exploitation of the commercial species, (3) ensuring a high quality of production from landings of the more valuable larger fish, (4) maintaining sustainable long-term biomass levels, and (5) avoiding unintended consequences on other components of the marine ecosystem.

Our findings indicate that excluding the trawlers from the coast for the Northern Adriatic Sea redistribute a part of the earnings gained from the fishing opportunities of the Italian fleet operating in the area from the trawling activity to the set netter activity when new grounds and larger fish become accessible to the latter. The trawler fishery is, however, still profitable over the entire five-year period, given the costs for fishing at the magnitude tested. Along this line, the tested mitigation plans are also shown to slightly improve the underlying stock status by reducing the fishing pressure, especially reducing the pressure on the coastal components of the harvested populations or on the vulnerable times of the species' life histories (Scarcella et al. 2014), especially for the common sole stock that is currently overfished. The juvenile sole are more likely to be found within these buffer areas. Although we expected that closing the area defined as the “sole sanctuary” (Fig. 1) would lead to protection of part of the sole spawning aggregation, our findings show that this effort is unlikely to benefit the trawl fishery because the underlying stock status is only slightly improved (given a lower fishing mortality

Table 1. Percent change compared to the baseline of the simulated total fishing pressure (hours per habitat surface area) and the landing weight footprint (landings per habitat surface area) over the spatial scenarios for groups of habitats (inside 6-nm buffer zone vs. outside; Holo. vs. non-Holo.).

Variable type	Variable	Habitat type	Baseline	Buffer 4 nm	Buffer 6 nm	Sole Sanctuary	Pomo Pit Ban	Exclude in all
Fishing pressure	F. effort	Out 6 nm	0	0.2	7.2	-0.6	-0.7	7.2
	F. effort	In 6 nm	0	-0.7	-5.8	0	0.2	-5.8
Landings weight	Hake	Out 6 nm	0	-0.1	2	-2.3	-3.9	0.8
	Hake	In 6 nm	0	-4.9	-100	-1.8	4.4	-100
	Sole	Out 6 nm	0	0.9	19.2	-1.2	-0.8	20
	Sole	In 6 nm	0	-1.8	-9.5	0	0.4	-3.3
	Mullet	Out 6 nm	0	1.7	6.8	1.7	3.4	8.6
	Mullet	In 6 nm	0	-11	-92.5	1.2	5.4	-92.5
	Mantis	Out 6 nm	0	0.3	7.5	0.8	0.3	9.3
Fishing pressure	F. effort	Non-Holo.	0	-0.4	-1.2	-0.1	-0.1	-1.1
	F. effort	Holo†	0	-1.5	-2.7	-2.3	-1	-4.5
Landings weight	Hake	Non-Holo.	0	-0.3	-1.9	-2.2	-3.5	-3
	Hake	Holo.	0	0.1	-1	-9.8	-3.9	-5.2
	Sole	Non-Holo.	0	-0.8	-1.8	-0.1	0.2	3.4
	Sole	Holo.	0	-4.1	-4.2	-2.8	-2.3	-4.5
	Mullet	Non-Holo.	0	0.2	-4.4	1.8	3.6	-2.6
	Mullet	Holo.	0	3.4	1.7	-5.5	5	-4.4
	Mantis	Non-Holo.	0	-1	-5.5	0.6	0.3	-4.2
Mantis	Holo.	0	-0.8	-4.8	0.9	-0.3	-4.6	

Notes: F. effort, fishing effort; Holo., Holothurian.

† Holo. comprises the habitats with the presence of the Holothurian-dominant group A, which are A000, AB00, ABC0, ABCD, A00D, A0C0, and A0CD merged on Fig. 1; non-Holo habitats otherwise.

and higher SSB), which is certainly not sufficient to ensure a sustainable exploitation of the Northern Adriatic common sole stock, and additional management steps are needed to reach the F_{MSY} European management targets according to the EU Common Fisheries Policy. Moreover, the effect also depends on an assumption that the sole population is able to quickly disperse over its known distribution. Hence, the fish not caught in some areas are eventually available elsewhere because the total effective fishing effort is only slightly reduced for trawlers, or is becoming accessible and caught by the set netters substituting to the trawlers, whereas a lower dispersion rate would downscale this effect. Meanwhile, an increase in sole SSB is unrelated to more recruits in the following years, as assumed by the simulations and in agreement with observations (STECF 2016). To manage the GSA 17 common sole stock, Scarcella et al. (2014) predicted that implementing a buffer at 6 nm to exclude trawlers would increase the overall sole SSB. While our current simulations do not show an effect of the same magnitude, this discrepancy shows the importance of underlying

assumptions to the projections. Firstly, projections in Scarcella et al. (2014) applied a constant exploitation pattern to the sole population in the forecasts. In contrast, our present model did not assume a constant exploitation pattern but an emerging pattern instead, one that depends on the catches occurring for the different size components of the population and on the spatial structure of the catches. Hence, even if our projections demonstrated lower catches of juvenile sole, this aspect did not lead to a large increase in SSB because the vessels eventually caught the bigger fish (making a higher profit out of it), a process that cannot be captured when applying the same F over the projection period. Secondly, Scarcella et al. (2014) assumed very little dispersion of the population (max 0.2% a month), whereas some of our current simulation assumes the redistribution of each size of the population over its full spatial extent every quarter. However, the ability of the population to disperse appears to be a crucial parameter about generalizing our outcomes because the place-based protection of stocks is not the best way to support highly mobile species, as

has also been confirmed by our results. Studying the mobility and the ability to disperse would reduce the uncertainty surrounding this aspect. Our results indicate that further investigations will be needed to precisely quantify the ability of the stocks to disperse or the mobility of the stocks to reduce the uncertainty of this effect on the efficiency of the spatial plans. However, management of the common sole stock clearly requires further actions because neither high dispersal nor low dispersal is sufficient to rebuild the stock. Furthermore, long-term changes in the distribution of the population and its size components can also occur for other causes (pollution and climate change), and the extent to which these changes will alter the current patterns and outcomes is to be clarified. Hence, these management actions should go beyond a strict spatial management when future yields are maintained at the current level. To avoid these issues and stop the stocks shrinking, managers might be tempted to design some more restrictive spatial plans, especially on the coastal components of the harvested populations or at vulnerable times in the species' life histories. Managers might also include set netters in the area restrictions or, alternatively, deploy more stringent management of the total amount of deployed fishing effort per vessel to let the stock rebuild and, ultimately, to improve the catch rate. The temptation to implement such fishery management options may also occur because the enforcement of spatial restrictions and special cases typically requires more resources.

Our findings are dependent on some limitations concerning the way the population dynamics are simulated. In particular, hake is known to prey on his own juvenile fish (Karlovac 1959, Jardas 1976), which could therefore reduce the growing population of hake. As a preliminary study, we have not accounted for such a density-dependent effect but, as shown in Angelini et al. (2016), this phenomenon should not impact the outcomes of this study. Cannibalism occurs in small percentages and it is practiced only by adult hake that represent a small portion of the population currently living in the Adriatic Sea (Angelini et al. 2016). Hence, the demersal fish and shellfish populations modeled here are assumed not linked by some sort of trophic interactions in single or multi-species contexts. The present demersal species are actually expected to interact only indirectly by

feeding on shared benthos communities, a depletion that is not handled in the current application. At this stage, the knowledge is too scarce to foresee what would be the implications of changing relative fish abundance also mediated by various (time and space) benthos depletion, further impacted by direct mortality from trawls (e.g., Hiddink et al. 2016). Other unknowns in the outcomes are the effects of these scenarios on other non-commercial species, such as by-catch species or species having their habitat disturbed by the bottom trawl fishery. This point represents a crucial step if it wants to develop a reliable and effective ecosystem approach to fishery (Garcia et al. 2003, Pikitch et al. 2004). As an ongoing development, we considered here the first steps of such an integrative approach by also incorporating the varying benthos habitats described by Santelli et al. (*in press*) that are fished upon by demersal fisheries in the area (also further discussed below).

Keeping in mind these model limitations, our findings indicate that some of the components of the spatial plan are efficient at providing some economic net gain in regard to mitigating trawling activity in a remote place like the Pomo Pit area. Given the large overcapacity of the Italian fishing fleet operating in the Adriatic Sea and the concomitant deterioration of its economic performance from lower volume of landings (STECF 2016), new spatial management is strongly necessary. The importance and the feasibility of reducing the fishing pressure on vulnerable areas of the marine habitat considered of biological interests, without adversely affecting the revenue from fish and even ensuring positive gain on some of the exploited stocks (hake and mullet), and which in turn, will reduce the unwanted catches, are clearly indicated. The simulations, however, assumed that the catch rates were not dependent on the abundance, and no decline in catch rate can occur when the effort concentrates on narrower areas. Given the low extent of the area closed compared to the entire available space for fishing (regardless of the other activities from other sector such as shipping), a congestion effect seems unlikely to occur in the Central Adriatic. Conversely, our findings suggest that such a crowding effect could have affected the vessels operating in the northern part of the Adriatic Sea if any vessels were being strongly limited by available space when the

buffer zones were implemented and may have occurred in the central areas where the Pomo Pit ban adjoins the 6-nm buffer area. Switching to the allowed practices in the trawler-free areas might be a valid alternative for fishermen wanting to continue fishing in more coastal places. The displacement of effort onto other areas in reaction to the restrictions, however, might create concerns regarding the side effects on biodiversity and aspects of the seafloor integrity. This is of particular importance when some of the habitats need protection because they are important to the life cycles of some of the commercial fish. In addition, closing areas for protective purposes not only should enhance fisheries but should also protect particular habitats and biodiversity when they are known to act as a buffer against changes in environmental conditions (Hilborn 2004). Our results indicate no side effects occur, especially in the Holothurian habitat, which may constitute a natural reserve for valuable fish but is not accessible for fishing due to the difficulty of operating on this type of bottom. These habitats are ultimately threatened by trawling fishermen who are incentivized to fish because of higher catch rates, a risk that may occur as soon as new fishing techniques are developed to overcome operating difficulties.

Spatial management can raise social concerns because this type of management can affect the local fishing communities more than it affects the more remote communities (e.g., Jones 2009), although both communities can live on the same shared resource, given the stock spatial connectivity and movements. Hence, an investigation should also look at the outcomes in terms of equity, to measure the size of the effects and to determine whether the same opportunities are offered to all the participants, given the placement of the closed areas and the underlying stock distribution (per valuable commercial category). Our results indicate that the income redistribution is somewhat equal overall within a given fishing activity (demersal otter trawl, demersal *rapido* trawl, and set netters in our case) but unequal among the different activities and harbor communities. Hence, the trawlers experience some economic losses from the permanent closures, which are not compensated in the long run from the better stock status. The results obtained at the scale of the individual vessel also show that some

individual trawlers are more affected by the spatial plans than others. This distributional issue might lead the practitioners or policy makers to account for unintended consequences in regard to ensuring the compliance of the fishing vessels to the regulation and to the final efficiency of the regulation (e.g., Bloomfield et al. 2012). Such spatial limitations in the fishing effort deployment would ultimately need a practical support and acceptance by the locally impacted stakeholders for a successful management.

This first, finely resolved, fishery model application in the Italian side of the Northern and Central Adriatic Sea (GSA 17) should provide technical inputs to assess how much the fishing sector is able to cope with management transformations. By handling a large amount of data in a unified bio-economic model (from benthos to fish, fisheries and spatial management), this should ultimately guarantee effective science-based inputs that will allow policy improvement and better governance for fisheries management and MSP that could apply in other places and extend across borders when it comes to competition for use of marine space (e.g., Bastardie et al. 2015). The model is able to incorporate the spatial and temporal details to obtain a necessary understanding of the integrated fisheries and the behavioral and resource dynamics that corresponds with the practical time and space scales that make sense as a starting place for the decision makers or policy makers. The fine spatial resolution furthermore allows for the support of local and regional MSP-related issues and impact assessment from the perspective of the fisheries. We therefore provide a comparison table (Table 2) summarizing the results of the evaluation analysis that should help identifying the key elements necessary for policy maker to choose the best policy option and are made available to them in a concise, understandable manner. Hence, the current application offers clear policy guidelines when it comes to quantify the extent of redistribution of economic profit when some fishing activities are excluded and, accordingly, new fishing grounds and larger fish are becoming accessible to the fishers. We demonstrate that all the impacted activities still remain profitable. The tested mitigation plans also slightly improve the sustainability of the harvesting by reducing the fishing pressure, especially on the coastal components of the harvested populations

Table 2. Operational summary of scenarios averaged outcomes compared to the baseline for the main indicators (stock status; fleet status; benthos status) at the five-year horizon time, and comments on the main source of remaining uncertainties.

Scenarios	Stock status		Fleet status				Benthos status	Uncertainties
	SSB	F/F_{MSY}	Effective effort	Net present value	Value per unit fuel	Income inequality	Fishing pressure	
Buffer 4 nm	Sole +5% Mullet +7% Mantis +2% Hake -1%	>1	Same total effort; effort displaced	Otter 0 Rapido -2% Net -2%	Otter 0 Rapido -2% Net -1%	Otter 0 Rapido 0 Net 0	No effort displaced on Holo. habitat	Stock assessment estimates; stock ability to disperse; uncertain fleet compliance
Buffer 6 nm	Sole +11% Mullet +15% Mantis +5% Hake -2%	>1	Less total effort; effort displaced	Otter -8% Rapido -8% Net -8%	Otter -3% Rapido -7% Net -7%	Otter 0 Rapido 0 Net 0	No effort displaced on Holo. habitat	Stock assessment estimates; stock ability to disperse; uncertain fleet compliance
Sole Sanctuary	Sole +1% Mullet +7% Mantis +2% Hake 0	>1	Same total effort; effort displaced	Otter 0 Rapido -2% Net 0	Otter 0 Rapido -1% Net 0	Otter 0 Rapido 0 Net 0	No effort displaced on Holo. habitat	Stock assessment estimates; stock ability to disperse; uncertain fleet compliance; possible effort attraction toward Holo. grounds
Pomo Pit Ban	Sole 0% Mullet +2% Mantis 0 Hake +8%	>1	Same total effort; effort displaced	Otter +3% Rapido 0 Net 0	Otter +2% Rapido 0 Net 0	Otter 0 Rapido 0 Net 0	No effort displaced on Holo. habitat	Stock assessment estimates; stock ability to disperse; uncertain fleet compliance
Exclude in all	Sole +11% Mullet +13% Mantis +5% Hake +8%	>1	Less total effort; effort displaced	Otter -5% Rapido -5% Net -5%	Otter -1% Rapido -5% Net -5%	Otter +2% Rapido +2% Net +1%	No effort displaced on Holo. habitat	Stock assessment estimates; stock ability to disperse; uncertain fleet compliance

Note: SSB, spawning stock biomass; Holo., Holothurian.

or at vulnerable times in the species' life histories. However, we conclude that the tested spatial management, and likely any spatial plan in the area, is helpful but not sufficient to ensure the sustainability of the exploitation of commercial fish stocks in the area; therefore, we demonstrate that additional management steps should be taken to reach the F_{MSY} European management targets according to the EU Common Fisheries Policy. We also show that spatial limitations in the fishing effort deployment also raise social concerns when trawlers are excluded from some areas without being able to compensate with larger catches or more valuable ones.

The main findings and their implications have therefore been discussed during a number of

meetings with fishers, administrative and scientists (during July 2016), and the stakeholder's view is required for this tool to contribute toward achieving sustainable fishing in the area on the basis of current modeling and subsequent scientific advices. Following the bio-economic impact assessment outcomes, the stakeholders also suggested the need to acquire additional information, especially on the hake and common sole stocks, to determine why conflicting signals emerged with the current assessment status for these stocks. Stakeholders also acknowledged that considerable benefits could be gained by collecting data on the ability to disperse of the stocks under study. Hence, the framework is to be developed further to include how the dynamics of the

fish populations may change in space and time, especially their ability to disperse, and the impacts of the fisheries on the benthic fauna communities and their dynamics, which is seen as an essential step forward to meet public demands for ecosystem-based fisheries management in the context of the MSP. The development of the model should aid decision-making by demonstrating the economic benefit of stock replenishment and sustainable harvesting when the ecological and economic impact of plausible fisherman decisions and the fishery management are combined before implementation. This is still relevant when evaluating the spatial occupation of smaller and larger marine areas by various marine sectors such as offshore gas platforms, other large marine constructions (e.g., breakwaters), mussel farms, and commercial shipping relative to their ecological–economic effects (e.g., restrictions in harvesting or resource protection) on fisheries, fishing communities, stocks, and other ecosystem components such as the benthic habitat impacts of fishery.

In such conditions, we specifically evaluated whether some benefits compensated for the added economic and ecological costs of the fishing efforts that were displaced to other areas and stocks, while also taking into consideration the interactions and constraints by the type of fishery management. At the same time, the model should determine whether displacing the effort does not harm sensitive or vulnerable benthic habitats. It is expected that practitioners should care at reducing the marginal effect of displacing one unit of effort on seafloor integrity while conserving the landings as far as possible. By applying the model that fit the local fisheries of the Adriatic region, practitioners could further develop tailored applications to their area for both understanding the fine dynamic of the interlinked fish and fisheries here, and, in the meantime, acquire a helicopter view of the outcomes when the small-scale (fishing) operations at sea are aggregated. Ultimately, the framework applied to the Adriatic or other areas should analyze and provide data with thematic reports/scenario on which the practitioners can rely on to project the fish stock population levels and fishery economy relevant to the ecoregion, while also including data from the neighboring countries (Slovenia and Croatia in the Adriatic). This framework for scenario evaluations

can be used to identify efficient fishing spatial planning, which then serves as the starting point for stakeholder involvement in the design, advisory, and decision process (Rassweiler et al. 2014). The data handling and modeling approach should contribute to assessments of the various trade-offs between landing value, habitat sensitivity, and fishing impacts (Jennings et al. 2012), also in context of broader MSP across borders when it comes to competition for use of marine space.

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