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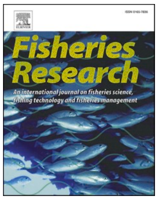

Trade-offs between spatial temporal closures and effort reduction measures to ensure fisheries sustainability

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ABSTRACT

Overexploitation has led to large scale declines in many fish stocks around the world with the 2030 United Nations agenda calling for more spatial management tools to achieve sustainability targets. However, without spatially explicit consideration of fisheries dynamics, assessment of management measures combining spatial temporal closures and effort reduction measures remain limited. This is particularly true when balancing population biomass recovery goals and their socioeconomic consequences. Using ISIS-Fish, the first spatially explicit bioeconomic model describing hake (*Merluccius merluccius*) fisheries in the Gulf of Lion, Mediterranean Sea, we investigated the consequences of individual spatial temporal closures and spatial closure network effects with all-at-one and gradual effort reduction measures. Their effectiveness in restoring the collapsed population and economic objectives were quantified to identify measures best suited for rebuilding population biomass, increasing catch weight, and maintaining revenue levels. While severe effort reduction was more effective in achieving population recovery goals than spatial temporal closures, these scenarios did not lead to an increase in catches until after five years. In contrast, spatial temporal closures failed to reach population recovery goals at any point during the simulation period, but impacted revenues the least. Simulated effort redistribution also led to greater depletion of juvenile hake, a pattern common elsewhere in the world. The present study illustrates how robust spatially explicit models may be used to evaluate the impacts of complex alternative management scenarios and to identify tradeoffs between biomass recovery, fishery viability, and the management equitability (and acceptability) between fishing fleets.

1. Introduction

European hake (*Merluccius merluccius*) is a demersal species that is widely distributed over the Northeast Atlantic shelf (Korta et al., 2015). Its range extends from as far south as Mauritania, with a southeastern extent of Turkey, and as far north as the west coast of Norway, just below Iceland, and extending into the Kattegat (Casey and Pereiro, 1995). It has a depth distribution of 10 to 1000 m (Colloca et al., 2013; Oliver and Massutí, 1995; Papaconstantinou and Stergiou, 1995) and serves as an ecologically structuring, top-down control species that links pelagic, demersal, and benthic trophic levels (Martín et al., 2019; Mellon-Duval et al., 2017; IUCN, 2015). European hake has a high socioeconomic importance (Sánchez-Lizaso et al., 2020; Abella et al., 2005) in the Mediterranean region, more so than in other northern European countries.

Since the 1970's, European hake fisheries have been monitored by two principal bodies: the International Council for Exploration of the Sea (ICES) and the General Fisheries Commission for the Mediterranean and Black Seas (GFCM) (IUCN, 2015; Korta et al., 2015). In the Atlantic, the ICES considers two hake stocks, both of which are considered stable or in recovery. While in the Mediterranean, the GFCM considers four large stocks, with several smaller management areas (STECF, 2022). All GFCM stocks have fishing mortality rates that exceed the maximum sustainable yield (FMSY) (STECF, 2022).

Mediterranean hake have been extensively studied over the past 50 years (Caddy, 2015; Aldebert and Carries, 1988). Where following a boom in fishing technological advancements in the 1960's and 1970's (Caddy, 2015), they began to suffer from high levels of fishing mortality, with decreasing trends in reproductive capacity, numbers of juveniles, and catch weights (STECF, 2020b; Samy-Kamal et al., 2014; Bănaru

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et al., 2013). This has particularly been blamed on the region's low selectivity and high juvenile hake catches (ages 0 and 1) (Caddy, 2015; Colloca et al., 2013; Aldebert et al., 1993).

Hake exploitation patterns, even between relatively close geographic areas in the Mediterranean Sea, are quite different between different fleets and gears (Aldebert et al., 1993; Lleonart, 1990). This has made the monitoring and application of uniform management measures exceedingly difficult. Aggravating this, data required to conduct migration studies for hake is lacking (Korta et al., 2015; De Pontual et al., 2013). Thus, the degree of inter-connectivity and mixing within and between both the ICES and GFCM stocks remain largely unknown. Historically, in the Mediterranean, each country handled their own management areas, despite having shared fishing grounds and markets (Vielmini et al., 2017; Damalas et al., 2015). In the Gulf of Lion in particular, several measures of control applying to the French fleet (e.g., time at sea, the number of vessels, and spatial temporal closures) were attempted from as early as 2008 (Dimarchopoulou et al., 2018; Cardinale et al., 2017). But these measures were not applicable to the Spanish fleet, or to vessels of other nations (Martín et al., 2019; Vielmini et al., 2017). Previously, the only measures which applied to all Mediterranean demersal fisheries included a restriction on the minimum cod-end mesh size that may be used by demersal fisheries (50 mm for square mesh, and 40 mm for diamond (FAO, 2009b)).

This was all changed in 2020 when the multi-annual Northwestern Mediterranean demersal fisheries management plan went into effect (EC, 2019a; EC, 2019b), which applied to all regional European nations. The main component of this management plan was to gradually apply effort reduction to trawlers on an incremental basis to reduce fishing morality at or below FMSY within 5 years time (by 2025). The intent of the gradual effort reduction measures was to allow for biomass recovery, while minimizing the impact on fishing opportunities (catch maintenance & projected revenues), and reducing juvenile catch (juvenile catch avoidance). But spatial temporal closures have been added for their potential to increase hake biomass and juvenile numbers (Tuset et al., 2021; Vilas et al., 2021), as well as to protect sensitive habitat areas (EC, 2021). The acceptability by stakeholders of these spatial temporal closures, and their location, remains a challenging issue (Tuset et al., 2021; Vilas et al., 2021; Nielsen et al., 2018; Cardinale et al., 2017; Morfin et al., 2016), although in the particular case of the Gulf of Lion, they were the result of co-construction efforts (Bourjea et al., 2019).

The Gulf of Lion demersal fisheries have only two species with a stock evaluation (EC, 2021): European hake and red mullet (*Mullus barbatus*) (EC, 2021), for which the effect of the plan can be monitored. Early studies have so far shown that spatial temporal closures, when applied to trawlers, have benefited red mullet (Dimarchopoulou et al., 2018), but very limited benefits have been seen with hake stock levels to date (STECF, 2022). Much research has also warned against the implementation of large scale spatial temporal closures without having a thorough understanding of their biological or socioeconomic effects (Tuset et al., 2021; Vilas et al., 2021; Morfin et al., 2016). But in the context of spatial heterogeneity in stock, and effort distribution, more tools that account explicitly for effort reallocation (van Putten et al., 2012) are needed (Mateo et al., 2017; Powers and Abeare, 2009).

The principal model (IAM) used in the current management evaluation by the European Scientific, Technical and Economic Committee for Fisheries (STECF) for the Northwest Mediterranean does not take space explicitly into account. This limits its ability to analyze the impact of spatial management measures, combined or not, on effort reduction (Tuset et al., 2021; Vilas et al., 2021; STECF, 2020a; Nielsen et al., 2018; Cardinale et al., 2017). Previously, the STECF has investigated employment of the spatially explicit bioeconomic models (STECF, 2017): SimFish (Bartelings et al., 2015) currently used in the North Sea flatfish and shrimp fisheries, TI-FishRent (Salz et al., 2011) that is employed in the North Sea saithe fisheries, and SMART (Russo et al., 2019), which was developed for the Italian demersal trawl fisheries (Bottom Otter Trawl). Each of these models is spatially explicit and can describe multi-fleet / multi-species dynamics both in the short and long term, while assessing management scenarios via simulation comparison and optimization. However, these models have not been applied in the Northwestern Mediterranean Sea, along the Spanish and French coasts due to either the amount of time required to implement them, knowledge gaps present in the study area, or their inability to be readily parameterized for the fisheries of the Mediterranean Sea.

We present the ISIS-Fish model parameterized for the hake fisheries in the Gulf of Lion, *MEDISIS*. Hake is the only species, which is explicitly defined in the model because spatial temporal closures have been found to work for the recovery of red mullet (Dimarchopoulou et al., 2018; Fiorentino et al., 2008). Previous models have also shown no implicit trophic (Mellon-Duval et al., 2017) or multivariate auto regressive relationship between the two species (Bensebaini et al., 2022). ISIS-Fish has previously been used in the assessment of the landing obligation in the Eastern English Channel (Lehuta and Vermard, 2023), and the evaluation of anchovy (*Engraulis encrasicolus*) management in the Bay of Biscay (Lehuta et al., 2013) with success. It has further been used in the Bay of Biscay to describe the impacts of spatial closures, and total allow catch limits, on the hake, common sole (*Solea solea*), and Norwegian lobster (*Nephrops norvegicus*) mixed fishery (Vigier et al., 2022; Provot et al., 2020; Drouineau et al., 2006). ISIS-Fish complements current assessment tools by allowing for the comparison of different spatial temporal closures and traditional effort management regulations at a monthly scale, while accounting for multiple métiers, fleets, and fishing strategies simultaneously. *MEDISIS* has been developed with the inclusion and active participation of fisher representatives, and sets out to investigate the relevance of alternative effort and spatial management measures (STECF, 2021; Wendling et al., 2019).

To select the best fitting measures for both addressing population restoration and industry objectives, we explored the consequences of multiple effort reduction scenarios together with spatial temporal closures that are currently in place in the Gulf of Lion. Both individual measures (effort reduction and spatial temporal closures) and scenarios that combine individual measures were assessed. Their effects differed depending on the scale at which the impacts are investigated for hake population (global, age, or maturity group) and for fleet (country, fishing strategy, or métier). The core paper focuses on the global aspects, and highlights the general effects seen with juvenile catch avoidance, while supplementary materials provides details at finer scales for the multi-fleet / multi-métier and age specific effects. Management scenarios were assessed in their ability to reduce juvenile catch, and to identify further effects on population dynamics via simulated annual biomass. We also assessed the industry's viability through simulating catch weight and revenues. Other species caught were considered for the revenue indices; however their population dynamics were not explicitly defined in the model. Trade-offs and scenario evaluations resulting from the analysis of these simulations are intended to promote compliance and to further contribute to meaningful discussion between scientists, stakeholders, and managers. This can lead to more sustainable, and effective, management of local fisheries in the future (Wendling et al., 2019; Nielsen et al., 2018; Pelletier et al., 2009).

2. Material and methods

This paper begins by briefly describing the regional fishery, and the model background, before moving into the parameterization of the fishery and the biological and population settings. Calibrations steps are highlighted, and are followed by model outputs, details on the alternative management scenarios assessed, and their evaluation. Only 14 of the 28 management scenarios assessed are presented in the results. These are considered representative of the overall effects that management scenario measures have on the fishing fleets, and métiers. Meanwhile, zone definitions, and more detailed information needed to reproduce the result outputs, are kept to the appendix sections. We conclude the method section with an uncertainty analysis, which utilizes a scenario comparison evaluation method to rank scenario robustness to recruitment, connectivity, and initial abundance assumptions.

2.1. Physical and fishing environment of hake in the Gulf of Lion

The Gulf of Lion is situated in the Northwestern Mediterranean Sea. It has a wave dominated continental shelf, with an average depth of 90 to 110 m (shown in blue, Fig. 1), and extends to a steep slope around the 200 m isobaths (Millot, 1990). The Gulf of Lion is incised by a number of submarine canyons (shown in pink, Fig. 1) and is characterized by a micro-tidal regime (Millot, 1990). Similar to other parts of the Mediterranean Sea, the demersal fisheries in the Gulf of Lion is diverse, with heterogeneous fishing fleets (Sánchez-Lizaso et al., 2020). The majority of which are small scale, multi-generational family businesses (Sánchez-Lizaso et al., 2020). However, much of the hake exploitation is attributed to fishing pressures exerted by the Spanish and French commercial fleets, rather than its numerous small scale fisheries (Farrugio, 2013; Aldebert, 1997), or recreational fishers (Dalleau et al., 2018). The catch composition of the Gulf of Lion demersal fisheries is not significantly dominated by a single species; hake are often caught alongside more than 167 other demersal and benthic taxa (Aldebert, 1997). To demonstrate this, for French trawlers and gillnetters together, European hake represented 8% of the total landed catches in 2017, while red mullet represented only 3%. These two species and the remaining top ten commercial taxa groups are shown in Appendix Fig. A.1 together with all other reported taxa grouped together as “Other”. These other taxa include 176 other species that were caught and sold in the region by the hake demersal fisheries. Total hake catch contribution by métier is dominated by French bottom trawlers, who represented 80% of the catch in 2018 (FAO, 2019). The rest are landed by French gillnetters (10%), Spanish bottom trawlers (9%), and Spanish longliners ($<$ 1%) (FAO, 2019).

2.2. Model description

ISIS-Fish is a spatialized, dynamic fisheries bioeconomic deterministic simulation model of intermediate complexity written in the Java programming language (Pelletier et al., 2009; Mahévas and Pelletier, 2004; https://www.ISIS-Fish.org). It has been used to assess the impact of management measures in a variety of fisheries across the northern Europe: in the Bay of Biscay (Vigier et al., 2022; Provot et al., 2020; Lehuta et al., 2013; Drouineau et al., 2006), English Channel (Lehuta and Vermard, 2023; Marchal et al., 2011), and the Baltic Sea (Kraus et al., 2009). It has a monthly time step and the spatial resolution (over a regular grid) is user defined, here a cell of 3’ x 3’ arc minutes (0.05° x 0.05°). ISIS-Fish incorporates three sub-models describing the population,

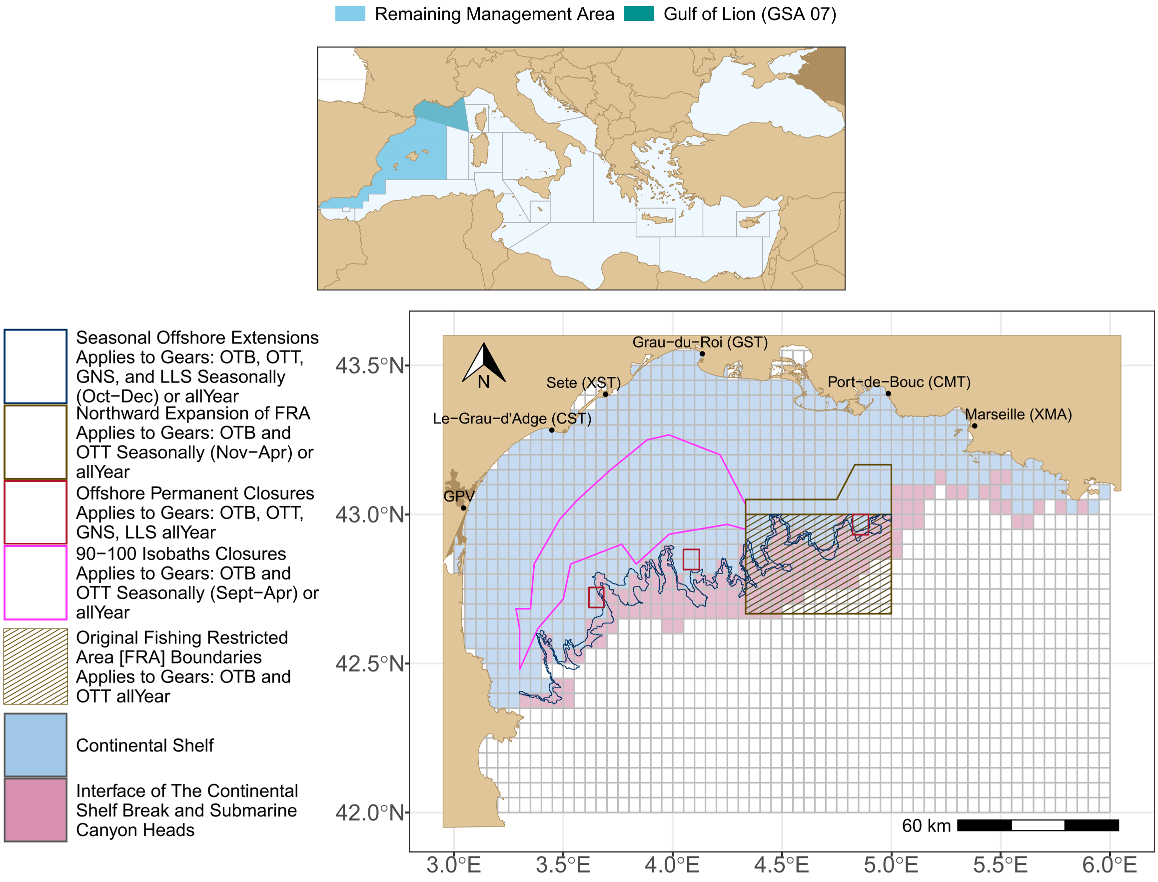

Fig. 1. A map of the Mediterranean Sea with the Northwestern Mediterranean management area to which the Gulf of Lion belongs (top). A detailed description of the two population zones defined for hake in this model (bottom): the continental shelf (Zone 1) and the interface of the continental slope and submarine canyon heads (Zone 2). Spatial temporal closure definitions used in the scenario evaluation steps are shown, which reflect actual closures that are in place within the Gulf of Lion. Implemented in 2018, the offshore closures include three permanent sites and one seasonal offshore extension (from October 15th to December 15th), which apply to all bottom gears as defined by LégiFrance, (2018). The original Fisheries Restricted Area (FRA) aiming to protect hake spawning aggregations was first established in 2009 following recommendation by the Food and Agriculture Organization (FAO) (FAO, 2009a). This closure only applies to bottom trawl gears: Twin otter trawls (OTT) and Bottom otter trawls (OTB). As part of the Multi annual northwestern Mediterranean demersal fisheries management plan enacted in 2020, two large seasonal closures were added to further reduce catches of juvenile hake. The Northward expansion of the FRA was applied from November to April in addition to closure of the 90-100 m isobaths from September to April. Both affected only OTB and OTT.

exploitation, and management dynamics. Interactions between the three sub-models occur where fishing, population, and/or management zones overlap. Unless specified through parameterized migration, or when a métier zone overlaps more than one population zone, each population zone is independent from the others.

2.3. Model characteristics and assumptions

General steps taken in the model parameterization are summarized in Fig. 2.

2.4. Fisheries settings

The fleet dynamics module of ISIS-Fish describes fishing effort distribution among fleets and métiers over the course of the year and informs parameters needed to standardize effort between métiers. French trawlers were grouped into fleet segments according to their length class (18–24 m, 24–40 m) and landing harbor (Appendix B, Table B.1). Six main harbors: Port la Nouvelle (GPV), Le Grau d′Agde (CST), Sète (XST), Le Grau du Roi (GST), Port de Bouc (CMT), Marseille (XMA), were retained along the French coast that reflects the major fishing grounds (Fig. 1). Vessels were assigned based on the shortest Euclidean distance between their principal landing harbor and main harbor (Fig. 1). Vessels of a given fleet were attached to a strategy (Appendix B, Table B.1), which described their time at sea (fishing days) for each month, and its distribution across métiers monthly according to logbook data (SIH, 2023).

Métiers were defined by the gear used, the target species, and the fishing ground visited, which depend on the fleet. The fishing grounds were defined by Vessel Monitoring System (VMS) data, where 90% of the fishing time of a given métier and fleet has been observed (SIH, 2023). We thereafter assume, in the model, that the fishing time of a métier-fleet is uniformly distributed over the cells of its fishing ground (Appendix B, Figs. B.1-B.23).

French gillnetters were not the primary target of the regional management plan, and a simpler segmentation was adopted where vessels using Anchored gillnets (GNS) and Trammel nets (GTR) were grouped together. Thus, we assumed a unique fleet strategy (French Gillnetters) and métier (GNS_FRA). The fishing grounds for gillnetters also covered most of the Gulf of Lion (Appendix Fig. B.1). Vessel descriptions, operating costs, principal port, and market analysis for the Spanish fleet were unavailable at the time of study, but we distinguished Spanish trawlers from longliners using the EU Fleet Register and VMS data for the period of 2015 – 2017 (SIH, 2023). Both Bottom otter trawls (OTB) and Twin otter trawls (OTT) gears were grouped together under one métier (OTB_ESP). Similarly, a métier (LLS_ESP) grouping Drifting longlines (LSD) and Stationary longlines (LLS) gear types was parameterized. We further defined each Spanish métier zone based on their VMS data for this period.

The catchability parameters (i.e., selectivity of gear per age (Appendix B, Table B.2) and target factor per métier (Appendix B, Table B.3)) were estimated by a General Linear Model (GLM) of Landings per Unit Effort (LPUE) as a function of métier, accounting for a yearly effect and derived from catch at length and expert knowledge. Trawlers were assumed to catch all age classes equally. Meanwhile, the gillnetters were found to target primarily ages 1 and 2, while longliners targeted ages 3 and older. The fleet dynamics model was set using 2015 – 2017 data, which is defined as the reference period by the management plan (STECF, 2019b). For projected effort, 2017 values were used.

Specific to ISIS-Fish, the monthly fishing mortality (F) is an emergent property and the model does not borrow the F from the assessment model split by age and fleet. Instead, fishing mortality at age and per population zone is computed monthly based on fishing time in the population zone, which is derived from the overlap between population zones and fishing grounds (assuming homogeneous effort within the fishing ground). Fishing time is then standardized by the catchability parameters per fleet and métiers and multiplied by an accessibility term to produce fishing mortality; which applies to population numbers of each age and in each population zone according to the Baranov equation (Pelletier et al., 2009).

$$F_{age,zone,month} = \sum_{met} acc_{age} * tar_{met} * Sel_{met,age} * E_{met,overlap,month} \tag{1}$$

where is the fishing mortality by age in a given population zone for the current is the availability of the age class to be fished by any métier, tar_{met} is the catchability of métier met, $Sel_{met,age}$ is the gear selectivity for the age class with the gear used by métier *met*, and is the fishing time of practice of the métier *met* in the cells overlapping the population zone at the current *month*.

Annual fishing mortality, comparable to the assessment model values and reference point, is computed *a posteriori*, at the end of each year, based on annual catch and biomass in January by reversing the Baranov

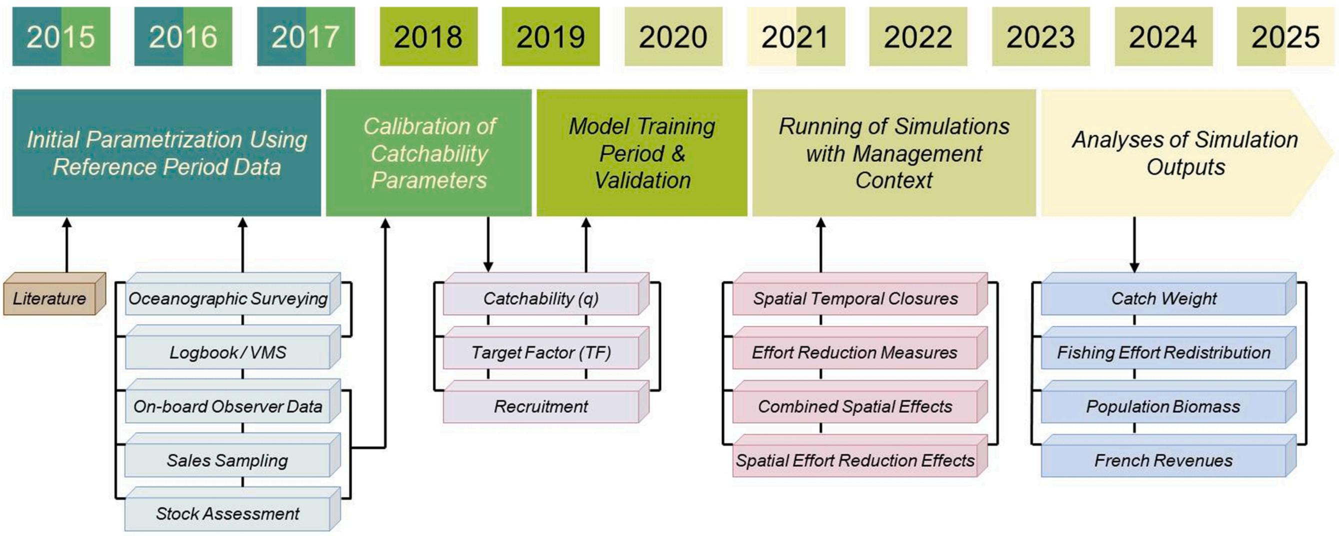

Fig. 2. : A workflow of the ISIS-Fish model parameterized for the Gulf of Lion hake fisheries, and its model parameterization steps. The initial parameterization and calibration were run over the reference years: 2015 – 2017, while the validation period ran from 2018 – 2019. For the forecast period, management was applied from 2020 – 2025. Analyses were carried out following the first and fifth year of implementation: 2021 and the first of the year in 2025.

equation.

2.5. Population settings

Hake population dynamics were age-structured following the assessment model: age 0 to age 5+ (Certain et al., 2018, Appendix C, Table C.1). Two population zones: 1) ContinentalShelf and 2) the interface of the continental slope and submarine canyon heads (ContinentalSlope) were defined from cartography of hake abundance-at-age using Mediterranean international bottom trawl survey (MEDITS) data (Jadaud, 1994) available over the 1994 – 2017 period (Fig. 1 & Appendix C, Figs. C.1 & C.2). The proportion of each age class allocated per population zone was also the same as those estimated by Wendling et al. (2019) in the GALION Project (Appendix C, Table C.1).

MEDITS is an oceanographic inter-annual trawl survey that takes place in June and has been running from 1994 to date. It follows a random stratified fix sampling design, which follows a depth (north-south) and east-west gradient. The biological components of this survey have allowed for the obtainment of length and weight measures, presence-absence data, sex ratio, and maturity measurements. These measurements have allowed for the computation of abundance indices, mortality coefficients, and spawning stock biomass indicators in the regional stock assessment evaluations for hake and red mullet. The MEDITS data can be obtained on request and mutual agreement from Jadaud (1994).

No local depletion within population zones (Fig. 1) were assumed, although fishing mortality was computed for each cell (each having 3’ x 3’ arc minute resolution) providing spatially heterogeneous fishing mortality. As in Vigier et al. (2022), it was also assumed that hake are mobile enough at a monthly scale within a population zone to replenish each fishing ground. Therefore, each month after fishing activity, hake abundance was uniformly redistributed within each population zone. We also assumed no migration across zones (Appendix C, Figs. C.1 & C.2) apart from the connectivity at the larval stage (i.e., age classes 1 through 5+ do not move between population zones, while recruitment is split across the two population zones (age class 0, Appendix C, Table C.2).

Recruitment (age-0) was gradually introduced along the year matching the observed seasonal catch patterns and split between the two population zones (Appendix Table C.2) depending on the connectivity assumptions (default of 83% in continental shelf and 17% in the interface of the continental slope and submarine canyon heads). Growth was assumed to follow Von Bertalanffy’s relationship (Mellon-Duval et al., 2010, Appendix C, Table C.3). Natural mortality assumptions were similar to those of the assessment model (Certain et al., 2018, Appendix Table C.3). Over the reference period, recruitment was set using estimates from the assessment model and for forecasting, we assumed recruitment to be independent of spawning stock biomass, and without inter annual variation.

2.6. Calibration

Twenty four parameters were still lacking or uncertain following the initial parameterization phase and needed to be assessed internally through model calibration. Calibration is a procedure that involves estimating the values of a set of selected parameters to enable the model to reproduce observations. Calibrated parameters were: fish accessibility at age (six parameters, Eq. 1), target factor (catchability of métier, Eq.1) for the French gillnetters, Spanish trawlers, and longliners (three parameters), and the proportion of recruits entering the fishery each quarter and year during the calibration years (constant over a quarter: 12 parameters). We also introduced a correction factor for annual recruitment values over the reference period (three parameters). Indeed, the assessment model from which recruitment values were borrowed assumes instantaneous recruitment at the beginning of the year, while our model considers progressive arrival. The correction factor aimed to compensate for this artifact. More detailed explanations can be found in Appendix D, Tables D.1 to D.5. To perform the calibration we review the available observations and define criteria comparing model outputs and observations (named global objective function (*OF*)) to be minimized. As observations over the period 2015 – 2017, we used various levels of aggregation of catch numbers at various levels of aggregation (i.e., at age, per gear, country, year (STECF, 2019a)), and stock assessment abundance values (Certain et al., 2018, Appendix D, Tables D.1 to D.5). The global objective function (*GOF*) was therefore multivariate (each element *i* in Eq. 2 being associated to a type of observation type or aggregation level) and computed as a sum of objective functions. Each objective function (*OF*) is the squared difference between observed and simulated values.

$$GOF = \sum_{i=1}^{1} OF_i = \sum_{i=1}^{I} \sum_{j=1}^{J} \left(Observed_{i,j} - Simulated_{i,j} \right)^2 \tag{2}$$

The 24 parameters were estimated in five steps using Latin hypercubes (McKay et al., 1979) of 5000 to 10000 simulations, each involving a different subset of the 24 parameters, and different OF elements (Appendix D, Tables D.1 to D.5)). This sequential approach was made necessary by the difficulty to minimize satisfyingly each element of the *OF* simultaneously. The predictive power of the model was assessed by comparing the same outputs to observations for the period 2018 – 2019 (Fig. 2).

2.7. Model outputs

Hake abundance and catches by age-class were computed for each month within the two population zones, while catches were also looked at for each fleet by métier and by gear. However, due to data limitations, economic outputs of the model were limited to gross revenues for the French fleet only. Following investigation of price difference by port and commercial category, which showed little variation, hake revenues were calculated as the product of catch weight and average monthly price. This was derived from port and commercial category sampling in 2017 (Appendix E, Fig. E.1). As hake is caught together with other species, we computed for the French fleet revenues not only derived from hake, but revenues from an additional nine species groups (Appendix E, Fig. E.2). All other species were grouped together (Appendix E, Fig. E.2). At the time of study, structural information on the population dynamics for these additional species groups were unavailable, and they could not be explicitly modeled. So instead, revenues were computed each month as the product of fishing effort by fleet, métier, and cell under each management scenario multiplied by the Value per Unit Effort (VPUE) following Appendix E, Eq. 3 observed for that métier during the same month in 2017 following Appendix E, Eq. 4. This followed the uniform effort distribution assumptions previously mentioned.

Thus when fishing effort is reallocated in space following a spatial closure, the value landed for the species was not only proportional to effort exerted, but also depended on the species catch distribution. We assumed that the biomass and monthly spatial distribution of these non-modeled species remained constant over the years. Simulations were run for 10 years starting in 2015 with management measures beginning on the 1st of January 2020. We distinguished three periods: the reference period 2015 – 2017, the validation period 2018 – 2019, and the forecast period 2020 –2025 (Fig. 2). Fishing effort distribution for each métier utilized the 2017 values throughout the validation and forecast periods. These were considered closer to the current fleet behavior than the mean of 2015 – 2017 reference years. For each year during the period 2018 – 2025, the total recruitment levels (in thousands, K) were set to the mean of 2015 – 2017 values (31296 K recruits) before splitting the recruits across time steps, as mentioned in Section 2.5.

2.8. Scenario evaluation

We present here 14 representative scenarios (*scenarios a, d, e, j, k, n,* *o, p, q, r, u, w, y, & aa*) out of 28 assessed by the study to describe how spatial temporal closures, effort reduction, and combining effort reduction with spatial temporal closures can impact management (Table 1). How their combination can affect scenario outcomes is also investigated by including scenarios involving single spatial closure effects, changes in the gears targeted by management, gradual versus all-at-once effort reduction measures, and whether or not spatial temporal closures remained permanent or seasonal. The Status Quo, where no measure was enforced, was simulated (*scenario a*). Effort reduction was implemented through reducing the number of fishing days for both fleets and métiers homogeneously with spatial temporal fleet distributions preserved. If effort reduction was applied gradually, it was done on an incremental basis until the maximum effort reduction was reached. Effort reduction targets were applied at the métier level, and were relative to the mean nominal effort exerted by the same métier (2015 – 2017). The full 28 simulated management scenarios can be found in Table 1. In the face of a spatial closure, we assumed that a métier's fishing effort was redistributed within remaining parts of their respective métier zone.

According to the regional management plan, objectives, and fishers' requests, several scales were investigated to assess how alternative management measures affect the hake population dynamics and industry. These were: biomass recovery (after 5 years), catch maintenance (after 5 years), projected revenues (after 5 years), juvenile catch avoidance (a goal of 20% less juvenile catches than mean juvenile catch of reference years (2015 – 2017) following 5 years), initial losses in catch (after first year), and initial losses in revenues (after first year). Total revenues were computed for all species as defined above. As a proxy for biomass recovery, biomass measurements were taken at the start of the year (before harvest and mortality were applied). Similarly, annual total catch weights (in kg) were taken at the start of the year (before harvest and mortality was applied) along with total revenues. Scenarios with the highest value were considered to be more effective than others. Indicators were computed relative to the mean indicator values simulated for the 2015 – 2017 reference period (STECF, 2020a) for both catch and biomass. However, revenues were compared against 2017 values, which were considered more relevant to projected years. For each of the 14 scenarios, these 6 indicators were re-scaled from 0 to 1, and contrasted using the R-library: *fmsb*. Line breaks are shown in percentage from 0 - 100 for easier interpretation, while the mean pattern effect for the represented 14 scenarios is shown as a shade at the center of each plot. More detailed results explaining the observed effect patterns are detailed in the appendix sections.

2.9. Uncertainty

Three uncertain processes were challenged to assess the diagnostic robustness of each management scenario. These were: 1) annual recruitment levels (described in Sections 2.5), 2) initial abundance values before the model simulation period began, and 3) recruitment split across population zones (described in Section 2.5). We used the mean 2015 – 2017 annual recruitment values for the assessment model, following the application of the calibrated correction factor for the primary hypothesis testing (31296 K recruits). Two alternative hypothesis values, which are considered less pessimistic, were also assessed. In the first, the first quartile of the 1998 – 2017 annual recruitment values from the assessment model was used (47298 K recruits); while the second utilized the average of the 1998 – 2017 values (64960 K recruits).

Initial abundance by age class was set equal to 2015 stock assessment report values (Certain et al., 2018), which was used for our primary hypothesis testing. A second initial abundance value was also tested that aimed to minimize the impact of under-sampling along the shelf border, which is less well covered by surveys and commercial catches on scenario values. In this parameterization, the initial abundance values for each age group within the Interface were doubled. Given limited information available on the hake spawning areas, larval dispersion, and nursery distribution, recruitment was split across the continental shelf and the interface of the continental slope and submarine canyon heads based on age class zero observations from MEDITS and stock evaluation (Certain et al., 2018), which is described in Section 2.5).

For our primary hypothesis testing, 17% of the recruits were allocated to the interface of the continental slope and submarine canyon heads, while 83% were placed within the continental shelf (as described in Section 2.5). Two alternative levels of dispersion were assessed. In which, the first assumed that juveniles are split more evenly between the two population zones, with 45% in the interface of the continental slope and submarine canyon heads, and 55% in the continental shelf. The second assumed a more unbalanced distribution of 3% within the interface of the continental slope and submarine canyon heads, and 97% along the continental shelf. By crossing the hypotheses of these three sources of uncertainty, we offered 18 alternative parameterizations, and simulated them for each management scenario assessed. Therefore 504 scenario combinations were simulated and evaluated (28 ×18).

In the results section, we present the corresponding effects of the assessed uncertainty for the representative 14 scenarios, while the full uncertainty results are available in Appendix F, Fig. F.1 The diagnostic for scenario robustness to uncertainty was drawn by investigating scenario rankings. Management scenarios were ranked with respect to their ability to increase catch weight, revenues, and biomass following the end of the simulation period in 2025 (the highest rank being the most desirable scenario). These rankings were then contrasted with the reference scenario (all parameters at initial values) and the impact of uncertainty evaluated by the range of ranks obtained for each management measure (the narrower, the more robust is the predicted outcome).

3. Results

3.1. Calibration / parameterization

New information about hake biology, particularly with regards to seasonality of recruitment was obtained via the calibration phase. Arrival rates of recruits were higher during the second and third trimester. The correction factor applied to each year's annual recruitment level ranged between 0.8 and 1.2. This resulted in the model's simulated total abundance (Appendix Fig. D.1), and abundance for age class 0 (Appendix Fig. D.2) not only matching the assessment model, but also the trends observed in abundance indices from MEDITS over the 2015 – 2019 periods. Some limitations remained however, in that the model could not reproduce some observed seasonal patterns in catch. The model progressively overestimated catch for the Spanish fleet (2015 – 2019), and the third quarter of 2016 globally. This was in addition to the last quarter across all years. Though the 2015 simulated annual catch for the French fleet was underestimated by 35% (Fig. 3), for each following year the relative difference between the observed and simulated values were minimal (levels between −2% and 9%, with a mean difference of 5%). The effects of overestimation in the Spanish catch were also minimized when investigating global catch (Spanish and French fleets together), with an absolute difference falling within 15% for all years (levels between −34% and 24%, and with a mean of 4%).

3.2. Scenario impacts

Juvenile catch avoidance was best achieved following effort reduction measures (*scenarios d, e, j, k, y, & aa*) (Fig. 4). However, combining spatial temporal closures with effort reduction (*scenarios y & aa*) offered little to no added benefits for hake management than effort reduction by itself. Spatial closures did not allow for catch maintenance or project a recovery of revenues after the five year period. When looked at individually (*scenarios n, o, p, q, r, u, & w*), also did not improve juvenile catch avoidance and showed not variation whether applied seasonally

Table 1
Scenario codes and names with explanations of gears affected, duration, and scenario category used in interpreting the simulation outputs. For gradual effort reduction measures, the cumulative value of the incremental effort reduction applied at the start of the year is shown in the scenario name. Effort reduction intervals are shown in scenario names and are applied from 2020 until the maximum effort reduction target has been reached.

Group	Sub	Scenario Type	Code	Scenario Name	Scenario Description	Gears
A	-	Fishing as Normal	a	Status Quo	Fishing as normal with fishing population parameters	-
B	B1	All-at-once Trawler Effort Reduction	b	Trawler_30_Red	The total numbers of fishing days are reduced by 30, 40 or 50% from 2017 intensities for all trawlers. The new effort levels are then split over the 12 month period for each management year.	FRA: OTT, OTB, OTM ESP: OTT, OTB
			d	Trawler_40_Red		
			f	Trawler_50_Red		
	B2	All-at-once Effort Applied to All Gears	c	AllGears_30_Red	The total numbers of fishing days are reduced by 30, 40 or 50% from 2017 intensities for all gears. The new effort levels are then split over the 12 month period for each management year.	All Gears
			e	AllGears_40_Red		
			g	AllGears_50_Red		
C	C1	Gradual Trawler Effort Reduction	h	Trawler_10_20_30	The total number of fishing days are reduced each year until a cumulative reduction of either 30, 40 or 50 % from 2017 intensities are reached for all trawlers. The new effort levels are then split over the 12 month period for each management year.	FRA: OTT, OTB, OTM ESP: OTT, OTB
			j	Trawler_10_17.5_25_32.5_40		
			l	Trawler_10_20_30_40_50		
	C2	Gradual Trawler Effort Reduction Applied to All Gears	i	AllGears_10_20_30	The total number of fishing days are reduced each year until a cumulative reduction of either 30, 40 or 50 % from 2017 intensities are reached for all gears. The new effort levels are then split over the 12 month period for each management year.	All Gears
			k	AllGears_10_17.5_25_32.5_40		
			m	AllGears_10_20_30_40_50		
D	D1	Seasonal Spatial Closure Single Effects	**o**	Northward_Expansion_of_FRA_Season	Seasonal spatial closures defined by existing law or suggested by the STECF	FRA: OTT, OTB, OTM ESP: OTT, OTB
			q	90-100_Isobath_Closures_Season		
			s	Offshore_Closures_Season	Spatial closures defined by existing law, but not enforced (Legifrance, 2018)	FRA: OTT, OTB, GNS ESP: OTT, OTB, LLS
	D2	Annual Spatial Closure Single Effects	**n**	Original_FRA_allYear	Annual spatial closures defined by existing law or suggested by the STECF	FRA: OTT, OTB, OTM ESP: OTT, OTB
			p	Northward_Expansion_of_FRA_allYear		
			r	90-100_Isobaths_Closures_allYear		
			t	Offshore_Closures_allYear	Spatial closures defined by existing law, but not enforced (Legifrance, 2018)	FRA: OTT, OTB, GNS ESP: OTT, OTB, LLS
E	E1	With 90-100m Isobaths Spatial Closure Combined Effects	**u**	Northward_Expansion_of_FRA_90-100m_Offshore_Closures_Combined	Spatial closure network effects investigated either seasonally or permanently	FRA: OTT, OTB, OTM ESP: OTT, OTB
			w	Northward_Expansion_of_FRA_90-100m_Offshore_allYear_Closures_Combined		All Gears
	E2	Without 90-100m Isobaths Spatial Closure Combined Effects	v	Northward_Expansion_of_FRA_Offshore_Closures_Combined	Alternative spatial closure network effect excluding 90-100 m isobaths closure definitions investigated seasonally or permanently.	FRA: OTT, OTB, OTM ESP: OTT, OTB
			x	Northward_Expansion_of_FRA_Offshore_allYear_Closures_Combined		All Gears
F	F1	Spatial Closure and Effort Reduction Combined Effects With the 90-100m Isobaths Closure	**y**	Combined_Red_10_17.5-40_Northward_Expansion_of_FRA_90-100m_Offshore_Closures	Investigation of scenario u and j together.	FRA: OTT, OTB, OTM ESP: OTT, OTB
			aa	Combined_Red_10_17.5-40_Northward_Expansion_of_FRA_90-100m_Offshore_Closures_allGears	Investigation of scenario u and k together.	All Gears
	F2	Spatial Closure and Effort Reduction Combined Effects Without the 90-100m Isobaths Closure	z	Combined_Red_10_17.5-40_Northward_Expansion_of_FRA_Offshore_Closures	Investigation of scenario v and j together.	FRA: OTT, OTB, OTM ESP: OTT, OTB
			bb	Combined_Red_10_17.5-40_Northward_Expansion_of_FRA_Offshore_Closures_allGears	Investigation of scenario v and k together.	FRA: OTT, OTB, OTM ESP: OTT, OTB

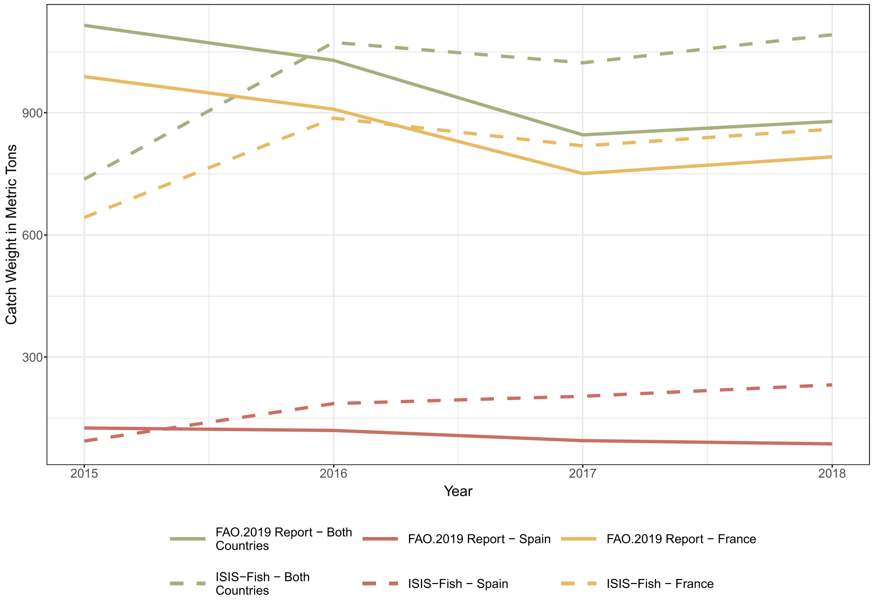

Fig. 3. A comparison of the simulated total annual catch weight for hake and stock assessment values for the same years presented by the GFCM WGSAD in FAO (2019) report. Simulation outputs from the ISIS-Fish model are shown as dashed lines, while the FAO (2019) report values are shown as solid lines. Total annual catch weights for hake in the Gulf of Lion (Both Countries) are shown in green, while French fleet catches are shown in yellow, and Spanish fleets in red.

(e.g., *scenario u*) or implemented for a full year duration (e.g., *scenario w*). Furthermore, all-at-once effort reduction measures (*scenario d & e*) had the best overall effect on population recovery, projected revenues, and historical catch maintenance goals, but at the expense of higher initial costs (Fig. 4).

Observed gains in revenues were also proportional to the level of effort reduction applied during the first year of implementation (Appendix F, Fig. F.2). After the first year, with the exception of *scenario e* (40% all-at-once effort reduction applied to all gears), all scenario measures were similar to, or led to increases in catch relative to historic levels (Fig. 5) compared to the Status Quo (*scenario a*). After five years of implementation, relative to the Status Quo, catches were considerably higher for all scenarios assessed (Fig. 6) except for *scenarios q* and *r* (closure of the 90–100 m isobaths).

The Spanish fleet was less impacted by effort reduction or spatial temporal closure measures than the French fleet (Figs. 5 & 6). If effort reduction measures were applied to trawlers exclusively, after five years, the Spanish fleet benefited from the reduced competition with the French trawlers as did the French gillnetters. This preferential benefit was reduced when applying effort reduction measures to all gears (*scenario e*). Where catches increased by 219% for the Spanish longliners and 22% for the Spanish trawlers, the French gillnetters saw gains of 15% and the French trawlers gains of 42%. This is opposed to the 31% and 81% relative increases in catch for the French trawlers and gillnetters respectively, and the 13% and 342% gains for the Spanish trawlers and longliners respectively. Thus, the disparity between national catches were greatly lessened.

Spatial temporal closures offered no added benefit on the global catch, without the inclusion of effort reduction for either investigated duration (*scenarios y & aa*, Figs. 5 & 6). Biomass under *scenarios q and r* (90–100 m isobaths spatial temporal closures) was less than under the Status Quo following both the first and last year of implementation. These patterns were driven by minimal increases in overall biomass within the interface of the continental slope and submarine canyon heads. Though spatial temporal closures had a minimal impact on the biomass within the continental shelf, when effort reduction was not applied (*scenarios n, o, p, q, r, u, v, & w*), after five years, spatial temporal closures within the interface of the continental slope and submarine canyon heads, led to further increases in annual biomass.

3.3. Uncertainty

All-at-once effort reduction measures were most robust (Fig. 7) in projecting global biomass, catch, and revenues following five years of implementation. This is in contrast to scenarios where effort reduction was applied gradually to all gears, which led to very large variability patterns in catch. Gradual effort reduction measures applied to all gears (*scenario k*), and scenarios combining spatial temporal closures together with gradual effort reduction applied to all gears (*scenario aa*), ranked second in their ability to increase biomass, but impacts to revenues were lessened when spatial closure were not applied. Under these scenarios, greater variation in catch was observed. This shows that recruitment and connectivity assumptions under scenarios where effort reduction was applied to all gears gradually, led to greater uncertainty when investigating at the global scale. Similarly, under the spatial closures single effect scenarios, greater variation in catch weight was observed than when spatial closures were combined as a network, but with differing degrees of robustness in their ability to increase biomass.

4. Discussion

4.1. Model limitations and strengths

In parameterizing the model, the most recent information from quantitative data and sector knowledge was used. However, the model was calibrated on 2015 – 2017 catch numbers, which is a relatively short training period in such a dynamic system. We expected the initial abundance settings to be a limitation of this study, but instead found only the connectivity and homogeneous dispersal assumptions mattered. These two assumptions may have led to an overestimation of juvenile availability, and subsequently catches as fishing intensity was redistributed along the coast. However, the impact of the assumption of uniform distribution of fishing effort in the fishing ground of each métier could not be evaluated and the direction of the effect is unpredictable. Indeed, accounting more finely for areas of effort concentration could have led to a greater effort release on juveniles when they overlapped with closures. However, it would have also provoked a larger report of the effort in the remaining open zones with possibly a higher impact. Thus the modeling process and uncertainty analysis subsequently evidenced gaps of

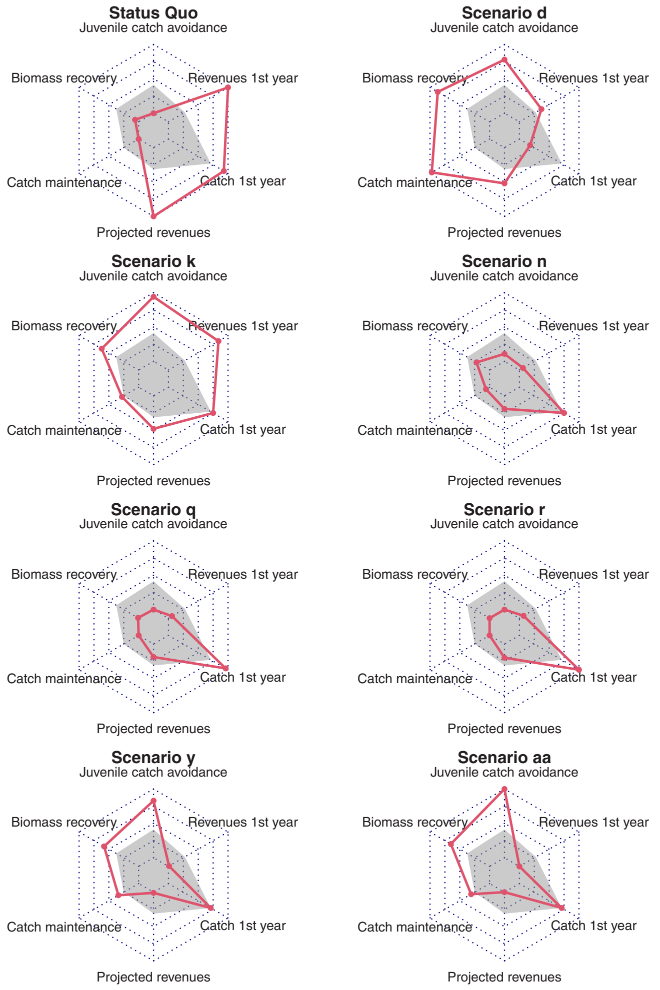

Fig. 4. : Evaluation of 6 indices, juvenile catch avoidance (after 5 years), catch maintenance (after 5 years), biomass recovery (after 5 years), projected revenues (after 5 years), initial loss of catch (after 1 year), and initial loss of revenues (after 1 year) for 14 representative scenarios. Values shown are scaled relative differences from the mean 2015 – 2017 reference values for all indices, except the projected revenues and initial loss of revenues. For projected revenues and initial loss of revenues, these are the scaled relative difference from 2017 values. Shown in gray, are the mean pattern effects of the 14 scenarios. Scenario definitions can be found in Table 1.

knowledge and uncertainties that should be considered a priority for future research.

Fishing effort redistribution is partly driven by economic factors (Powers and Abeare, 2009), such as fishing duration, port distance, and fuel costs (Damalas et al., 2015; Prellezo et al., 2012), which were not explicit in the model. Without this knowledge, it is therefore possible that our model's ability to realistically reflect fishing effort redistribution is impaired. But we do offer post-hoc conservative effort redistribution mapping, and effort redistribution behavior was discussed with fishers and deemed realistic (Appendix F, Figs. F.3-F.7). This realism was later confirmed by VMS derived effort distribution maps obtained before and after closure implementation (STECF, 2023a).

At the present time, there is too limited information to address the spatial heterogeneity, mobility, or origin of hake in the Gulf of Lion. The data required to assess the migration, and immigration, between hake stocks within the Northwestern Mediterranean Sea, as well as with other Mediterranean and Atlantic stocks is also too limited. However, hake have been found to be highly mobile in the Bay of Biscay by Korta et al. (2015), as well as in the northern stocks managed by the ICES. Management also considers that the Northwestern Mediterranean stock extends from the South of Spain to the Southeastern border of France. So, the conservative assumption of a homogeneous dispersal pattern used here is supported by our current understanding of hake spatial distribution patterns.

Much of the knowledge present in the Gulf of Lion is biased towards recruits and early stage juveniles (Hidalgo et al., 2020) with little information available on the ontogenetic stages from the ecological and fisheries perspectives prior to maturation (Hidalgo et al., 2020). It is assumed that after hake reaches the first year of maturation they are distributed everywhere along the continental shelf. Further dissemination of hake distribution patterns by life stage, or migratory behavior, therefore requires further study. Utilizing scientific survey data, we assessed the robustness of each scenario measure to multiple connectivity and recruitment level assumptions. We formulated two population zones based on the findings of other studies who have reported hake to be dispersed across the entire Gulf of Lion (Ragonese, 2009), with juvenile hake distributions to be in higher concentration along the continental shelf (Certain et al., 2018; Caddy, 2015; Aldebert, 1997).

Studies have also found that while hake nursery grounds tended to coincide with the regions' specified closures, biomass just before the continental shelf break was very low and ichthyoplankton connectivity and dispersal were often reliant on marine circulation patterns (Hidalgo et al., 2019; Druon et al., 2015). Model simulations allowed for local depletion of juvenile individuals under the spatial temporal closure scenarios. But this effect was minimized by the relatively short time step (one month), which prevented accumulated local depletion. As a result, the current model assumptions and population zone definitions may have underestimated the effects of spatial closures. It is also expected

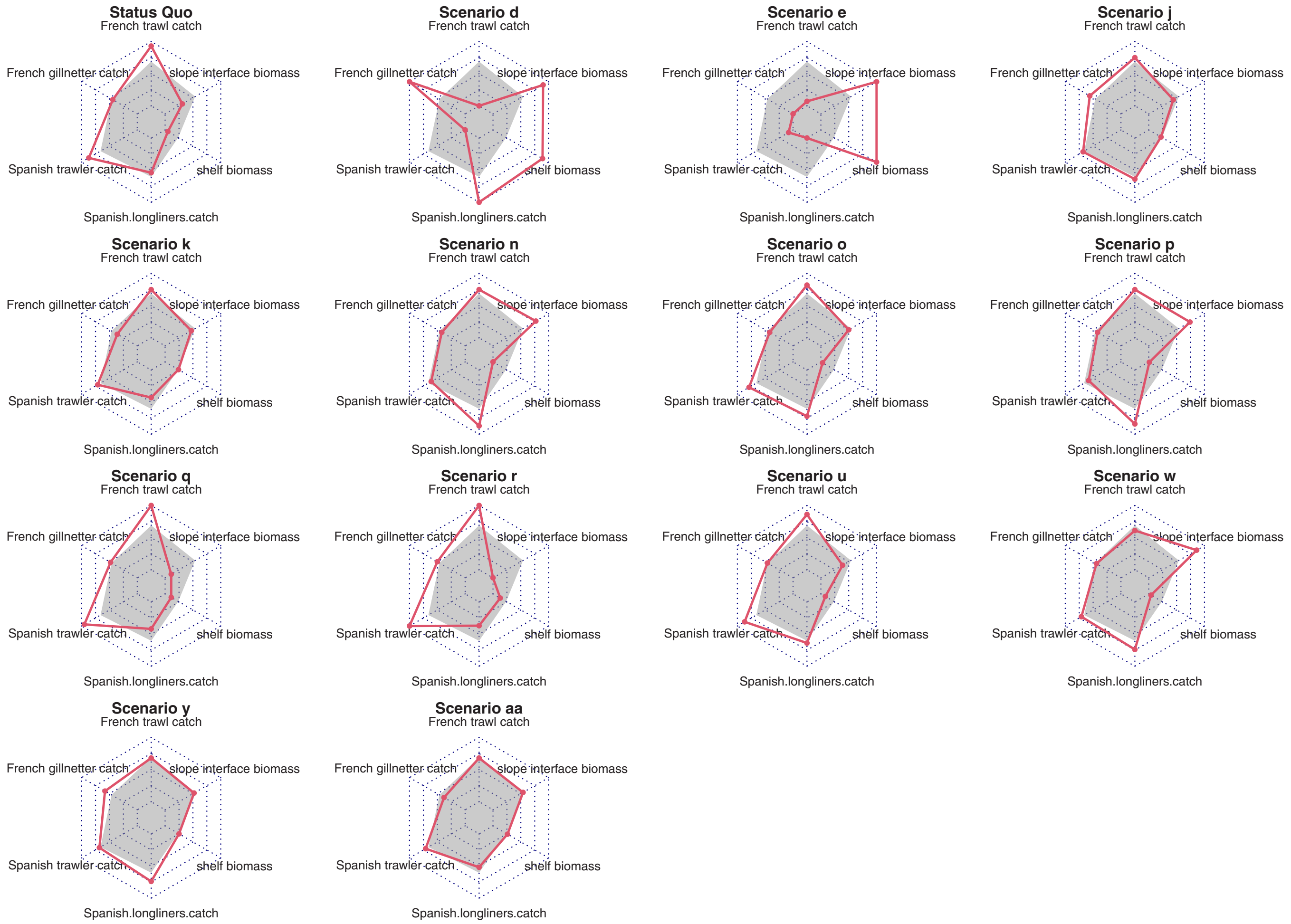

Fig. 5. : Evaluation of 6 indices (French trawler catch, French gillnetter catch, Spanish trawler catch, Spanish longliner catch, shelf biomass, and slope interface biomass), which illustrate how 14 representative management scenarios can impact fleets and population zones differently following one year of implementation. Values shown are scaled relative differences from the mean 2015 – 2017 reference values for all indices. Shown in gray, are the mean pattern effects of the 14 scenarios. Scenario definitions can be found in Table 1.

that more precise biological zone definitions allowing for accumulated local depletion would increase their effectiveness. Despite our expectation that some species would benefit from effort release, only hake was accounted for in the model. Subsequently, the monthly spatial distributions and stock levels of other species were assumed to follow 2017 levels, which would represent a status quo ante scenario.

4.2. Management measure efficiency

The scenarios simulations revealed that all-at-once effort reduction measures were the most effective in increasing catches in the long term, but with greatest initial losses. Increases in catch weight after five years' time were also proportional to the degree of which effort reduction was applied from the first year, especially when not combined with spatial temporal closures (Appendix Fig. F.8, *scenarios b, c, d, e, f, g, h, & i*). This varies slightly from Hopf et al. (2016), who found dramatic declines in catch weight early on, and greater gains in future years, when using marine reserves to restore historic catch levels. Effort reduction measures may therefore offer a more immediate response than spatial temporal closures, albeit at the risk of greater financial losses.

While we had different scenario contexts and methodology, these findings are similar to those of Russo et al. (2019), whom, using SMART parameterized for the central Mediterranean Sea trawl fisheries, found that only a complete halt in trawl fishing during the summer months improved biomass in the long-term. Furthermore, Russo et al. (2019) found that Fisheries Restricted Area (FRA) and FRA network scenarios initially increased spawning Stock Biomass (SSB) levels before it began dropping, but not below current levels (i.e., not improved, but still overly exploited). The effects of spatial temporal closures, as presented here in the Gulf of Lion, should therefore be considered a warning to decision makers. Spatial temporal closures should not be used as stand-alone management measures. Instead, they should be used as a way to offset financial losses or to address management objectives other than hake recovery. To date fishers have also respected the spatial closure measures, preferring these over increased mesh size. Future work with fishers should also be considered to minimize, where possible, the economic repercussions of additional restrictions so that compliance levels are maintained.

Spatial temporal closures are often considered as a cure all, especially with the documented benefits they provide in improving nursery ground conditions, increasing stock biomass, and protecting vulnerable species (Marcos et al., 2021; Tuset et al., 2021; Vilas et al., 2021; Dimarchopoulou et al., 2018). But the spatial temporal closures implemented with our simulation model were not found to be particularly useful in hake population recovery (at least not within 5 years' time), especially when designating large seasonal closures not associated with equivalent effort reduction measures, whether applied seasonally or annually. Low effectiveness of spatial closures in restoring population biomass were also seen when looking at wide scale placements of fixed Marine Protected Area (MPA)s to protect spawning of tuna in the Pacific

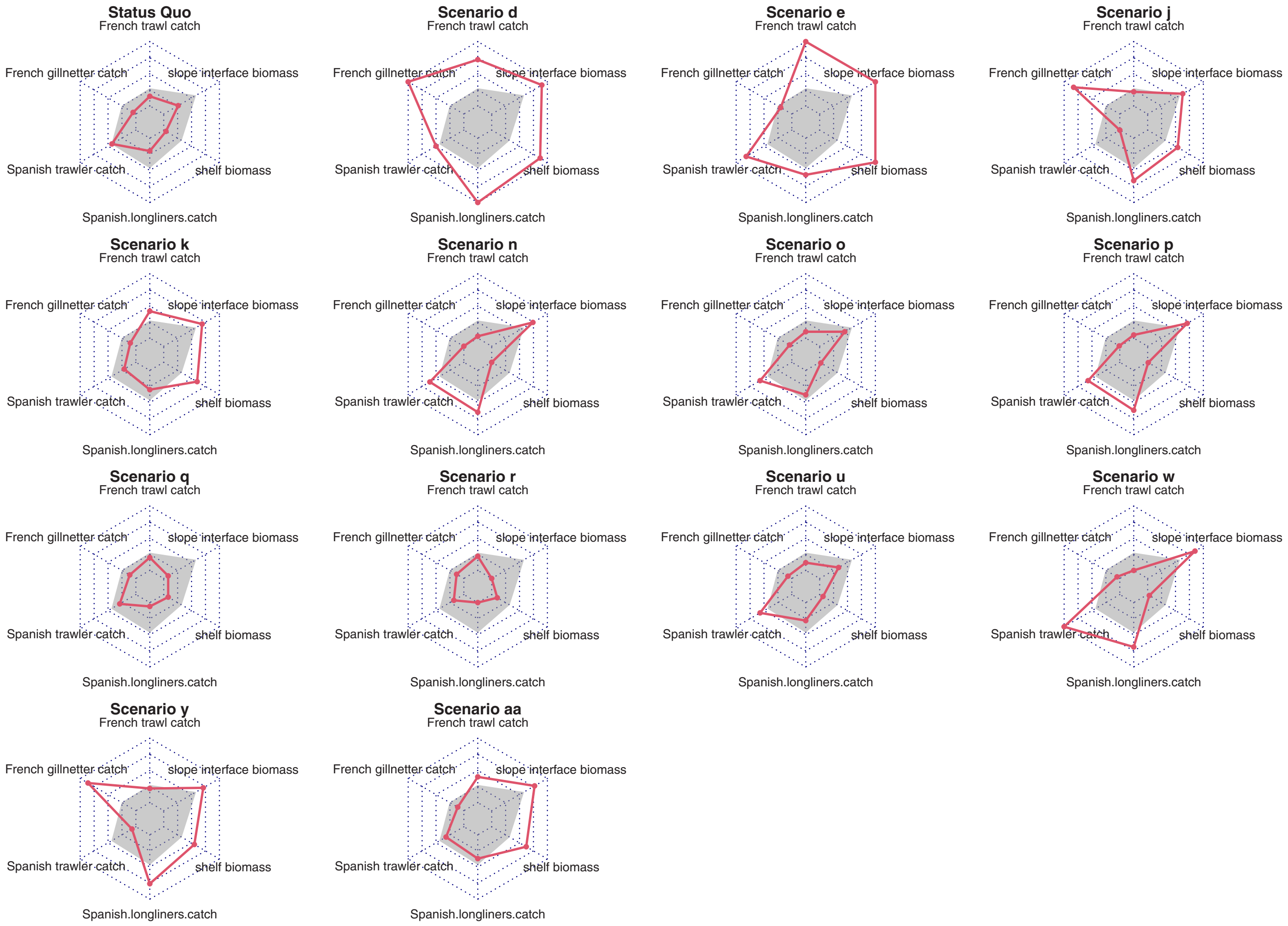

Fig. 6. : Evaluation of 6 indices (French trawler catch, French gillnetter catch, Spanish trawler catch, Spanish longliner catch, shelf biomass, and slope interface biomass), which illustrate how 14 representative management scenarios can impact fleets and population zones differently following five years of implementation. Values shown are scaled relative differences from the mean 2015 – 2017 reference values for all indices. Shown in gray, are the mean pattern effects of the 14 scenarios. Scenario definitions can be found in Table 1.

Ocean (Hampton et al., 2023). Given that both tuna and hake have similar ecological and functional roles, in that they are highly mobile predators (Mellon-Duval et al., 2017; Korta et al., 2015), this could partially explain what was observed here.

The reallocation of fishing effort likely contributed the most to the failure of spatial closures in reaching management objectives. Fishing effort was redistributed just outside the closure boundaries, which led to increases in catch that exceeded recovery rates (Appendix F, Figs F.3-F.7). This is similar to Abdou et al. (2016), who found that fishing effort redistribution in response to spatial temporal closures led to increases in catch weight rather than population recovery if management measures did not include further effort reduction in the Gulf of Gabes. Without reduction applied, fishing effort redistribution under spatial temporal closures, particularly with the closure of the 90–100 m isobaths, was also counter productive. For example, within the interface of the continental slope and submarine canyon heads, annual biomass after five years of implementation was negatively impacted under the closure of the 90–100 m isobaths (Appendix F, Fig. F.9). This resulted in declines in total biomass up to 21% (*scenario r*) relative to the Status Quo, which also suggests a reduction of 20% in juvenile catch is unlikely to be reached under current management objectives.

Adding effort reduction measures to the spatial closure network also provided little benefit to biomass recovery goals, and did not lead to a change in scenario ranking. The exception was *scenario x*, which was a permanent spatial closure network scenario that excluded closing the 90–100 m isobaths (Appendix Fig. F.9). This may be explained more by the extreme fishing pressure experienced by both ends of the population scale (mature individuals and juveniles), than the closures themselves (Caddy, 2015). However, in finding alternative solutions to seasonal closures for trawlers (*scenarios o, q, s, u, & w*), more creative solutions need to be relied on. Alternative closure durations that allow for more effective resting regimes, or where a total stop to fishing occurs within specific zones may be one way of achieving this.

Periodically Harvested Closure (PHC)s, which were investigated by Goetze et al. (2018) in Micronesia, had great success in short term recovery goals in that PHCs led to greater catches and recovered population biomass (Goetze et al., 2018). Furthermore, when closures are applied for longer duration and are well enforced (Tuset et al., 2021), these effects are expected to increase. However, Goetze et al. (2018) cautioned against larger stock removals during authorized harvests periods, which would undoubtedly be the case in the Gulf of Lion, given the high fishing efficiencies of the current fleets. Another solution could therefore be to apply dynamic closures, which other studies have found to be more effective in protecting both economic and highly mobile species such as migratory sharks in the east Mediterranean (Zemah-Shamir et al., 2023). However, the apparent stability in the hake population spatial distribution within the Gulf of Lion does not encourage this approach.

It is also possible that the time required for the recovery of hake population biomass was too short in the model to see positive effects of

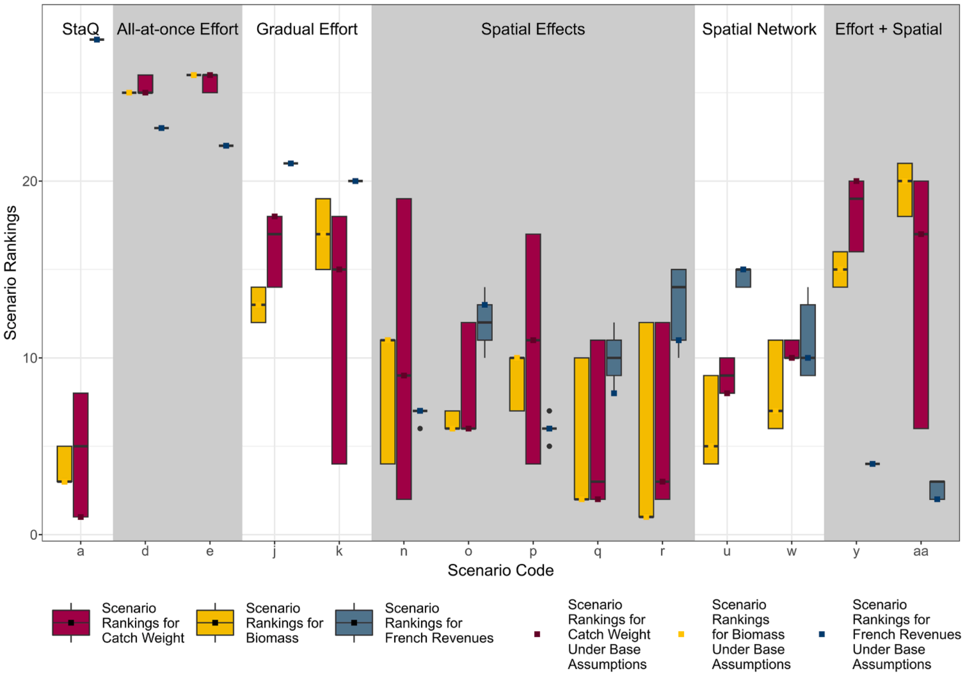

Fig. 7. **:** Modeled robustness of the 14 representative scenarios to uncertainties in recruitment, connectivity between population zones, and initial abundance. Hake catch weight (in red) and population biomass (in yellow) is shown after five years of enforcement. French revenues for both hake and other species under 2017 dynamics are shown (in blue). Catch weight values include both the Spanish and French fleets together. The scenario ranks under the model's base assumptions (reference values): spatial distribution, recruitment, and the initial abundance are shown as bullets. For each of the 14 scenarios, the box shows the range of the scenario ranks accounting for the 18 combinations of uncertainty values. StaQ includes the Status Quo scenario, while All-at-once Effort includes all-at-once effort reduction measures. Gradual Effort includes gradual effort reduction measures and Spatial Effects all spatial closure single effect scenarios. Lastly, Spatial Network includes combined spatial closure effects, while Effort + Spatial includes the assessed effort reduction scenarios combined with the spatial temporal closures. The position of the model's base assumptions (bullet) and the height of the box are used to assess the robustness of the scenario. Scenarios with higher rankings are positioned at the top and the most robust scenarios are considered to have shorter boxes. The median rank over the 18 values is the horizontal black line of each box.

spatial temporal closures (Hopf et al., 2016). More generally, our model did not assess ecological health or trophic interactions that could have affected population biomass recovery for hake as tertiary consumer. Any observed gains in population biomass under effort reduction measures, and lags observed under spatial temporal closures were instead solely explained by fleet dynamics and mortality alone. Thus ecological factors are expected to further limit, or improve, the biomass recovery time than what we have suggested. It is also possible that to see stabilizing effects of spatial temporal closures in the Gulf of Lion, modeling of essential habitat definitions is necessary (Marcos et al., 2021; Tuset et al., 2021; Vilas et al., 2021; Morfin et al., 2016). But as discussed above, more fine scale studies investigating habitat and aggregation zones are needed to define more meaningful biological zones, and to identify the connectivity rate at age for the region.

Without more detailed information on larval or juvenile dispersal in the Gulf of lion, we relied on the uncertainty analysis to assess the impact of dispersal assumptions on closure effects. The effect of these dispersal assumptions resulted in greater variation in future catch and biomass recovery levels under spatial closure measures. Furthermore, scenarios combining spatial temporal closures with effort reduction had a larger degree of uncertainty than scenarios where only effort reduction was applied, which suggests a greater sensitivity to the connectivity and monthly dispersal assumptions made here. However, we demonstrated that while spatial temporal closures were the most variable in response, the ranking of management measure benefits remained unchanged. This higher variability when employing spatial measures is contrary to what is frequently shown (Yamazaki et al., 2015; Stelzenmüller et al., 2008). Though the mentioned studies did not account for uncertainty in fisheries related spatial processes, such as fleet dynamics or recruitment dispersal, as we have done here.

4.3. *Management trade-offs*

It was expected that gradual effort reduction would have less impact on biomass in the short term than all-at-once effort reduction, mainly because they reached the same target after five years compared to the very first year for the all-at-once scenarios. However, management diagnostics cannot be limited to biological conservation issues. Management trade-offs combining biological conservation targets, and maintaining the fishery viability, with particular caution to the transition period, should be considered (O'Keefe et al., 2014). By reducing fishing effort all-at-once, severe socioeconomic impacts on the fisheries in the short term would occur. But in hindsight these measures would have led to greater returns in population biomass and catch weights. A good parallel with haddock is described by Apollonio (2015), where they introduce a hierarchical structure of evaluation to ordering management processes. They detail the trade-offs between the functional response of management, the integration of a species' population dynamics, and the ecological function or economic targets by fisheries.

Total revenues for the French fleet also shed another light on scenario impacts, as gains were proportional to the amount of effort reduction applied in the first year. But as the population dynamics for species other than hake are not directly considered by the model, and prices are, in truth, not constant over time, caution must be taken when interpreting these results at face value. Nonetheless, they illustrate the usual trade-off of mixed fisheries where measures placed on one species could either be beneficial or detrimental to the rest of the species portfolio (Moore et al., 2021).

Analysis of spatial closures themselves also showed a country bias in their consequences, where France was more impacted by management than Spain. Similarly, French gillnetters, together with Spanish longliners, stood to gain the most from effort reduction measures. Our scenario assessment suggests that uniform effort reduction across all gears could be most appropriate. This would also provide a more evenly dispersed responsibility across the fleets and between nations and improve their acceptability. Our study further showed that biomass can be increased within a five-year period, as opposed to a 10 to 25 year period under scenario measures only affecting trawlers, when applied to all gears. By forcing effort reduction to all vessels as opposed to removal of the largest three trawlers present in the fishery in Lleonart et al. (2003), we were also able to assess the effects of effort redistribution at finer scales (Appendix F, Figs. F.3–7).

Our results draw attention to the conflicts between the time frame set by the regional management plan for reaching management objectives (i.e., juvenile catch avoidance and stock biomass recovery within five years), and what is achievable under moderate effort reduction scenarios or spatial temporal closures. Though we found spatial temporal closures to be ineffective in reaching management goals for hake, it is still reasonable to assume that effort reduction, possibly together with meaningfully placed spatial temporal closures, will benefit hake and other species. However, even after three years of applying both effort reduction and spatial temporal closure measures, the hake stocks have not improved in the region (STECF, 2023b).

ISIS-Fish is a modeling platform, which is used to describe mixed fisheries dynamics (with multiple species and multiple fleets), and can evaluate the impacts of spatial management with various alternative parameterization. The present work focused on the Gulf of Lion hake fisheries, which is only a small representation of a larger management area considered (Fig. 1). But as further data becomes available, the inclusion of other species would greatly benefit this ISIS-Fish application, and provide assessment of management scenarios at a broader ecosystem scale. This early work may therefore serve as a framework to further explore fleet dynamic relationships, not only in the Gulf of Lion, but in other parts of the northwestern Mediterranean Sea and beyond. This is especially true given that the hake stock assessments are now performed at northwestern Mediterranean scale (STECF, 2023b). Our findings may also be of use to future management plans, and provide managers and other stakeholders with more educated choices going forward. Additional studies should prioritize investigation of biological relationships in connectivity and recruitment for hake and more common species in the region. Such knowledge would indubitably contribute to increase model realism and aid in identifying more clearly population zone definitions, as well as critical habitat areas that require protection.

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CRediT authorship contribution statement

Sandrine Vaz: Writing – review & editing, Visualization, Validation, Supervision, Resources, Funding acquisition, Conceptualization. **Stephanie Christine Hopkins:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sigrid Lehuta:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Stephanie Mahevas:** Writing – review & editing, Visualization, Validation, Supervision, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Stephanie Hopkins reports financial support was provided by Occitanie Region.

Data Availability

ISIS-Fish settings, zone definitions, and script files as well as R Markdown codes used in the analyses are available at (https://github.com/SHopkins2024/MEDISIS) (Hopkins et al., 2024).

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2024.106998.

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