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A simulation-based approach to assess sensitivity and robustness of fisheries management indicators for the pelagic fishery in the Bay of Biscay

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Abstract:

Indicators are widely promoted as means to monitor ecosystem status or to evaluate fisheries management performance. "Which indicators are most relevant as decision-support tools in fisheries management?" still remains a topical question. Indicators should be metrics related to fish populations and fleets and should be sensitive to management strategies. However, given the complexity of the processes involved, it is often difficult to unequivocally interpret variations in metrics. A simulation approach was used to study metric properties and to identify robust and relevant fishery indicators. By applying sensitivity analysis methods, simulation designs were built that cross a variety of management scenarios and uncertainty hypotheses. Bio-economic outputs were simulated using a mechanistic model (ISIS-Fish), and their properties were statistically analyzed. This approach was applied to the pelagic fishery of the Bay of Biscay. The analysis of metric properties highlighted the major factors driving variations in each metric and identified the important sources of uncertainty that need to be reduced to allow the use of metrics as indicators. Although very few metrics gave robust indications of management performance, sensitivity indices evidenced how management performances could be improved, and spatially disaggregated metrics provided insights into the mechanisms underlying management performance.

Résumé:

L'utilisation d'indicateurs est largement préconisée pour le suivi et l'évaluation d'impact de stratégies de gestion sur les pêcheries. « Quels indicateurs permettent d'appuyer les décisions de gestion des pêcheries? » reste une question d'actualité. Ces indicateurs doivent être des métriques décrivant populations et flottilles et sensibles aux stratégies de gestion implémentées. Néanmoins, la complexité des mécanismes impliqués, rend l'interprétation des variations d'une métrique souvent ambigüe. Nous proposons une approche par simulation pour étudier les propriétés de métriques et sélectionner des indicateurs de pêcherie pertinents et robustes. En appliquant des méthodes d'analyse de sensibilité, nous avons construit des plans de simulation qui croisent différentes mesures de gestion et sources d'incertitude. Le modèle mécaniste ISIS-Fish est utilisé pour simuler les métriques bioéconomiques dont les propriétés sont ensuite statistiquement analysées. Cette approche est appliquée à la pêcherie pélagique du Golfe de Gascogne. Elle a permis de mettre en évidence les facteurs principaux à l'origine des variations de valeur des métriques et d'identifier les sources d'incertitudes à réduire pour permettre leur utilisation comme indicateurs. Bien que peu de métriques informent de manière robuste sur la performance des mesures testées, les indices de sensibilité fournissent des voies d'amélioration de ces performances et certaines métriques spatialisées améliorent la compréhension des mécanismes induits par les règlementations.

Introduction

Technical measures, and among them Marine Protected Areas (MPA), are advocated more and more, not only as conservation measures, but also as management tools to help preserve ecosystem structure and quality as well as to enhance fishery yields (Babcock et al. 2005; Pelletier et al. 2005; Field et al. 2006; Stelzenmuller et al. 2007, but see Hart 2006; Sanchirico et al. 2006). Selecting an appropriate spatial management measure to reach ecosystem-management objectives and assessing its performance over time requires keeping track of every component of a system, preferably at high spatial resolution. Many indicators have been proposed in the recent literature as tools to assist with monitoring requirements. Some indicator frameworks have also been proposed which combine indicators and their trends into operational tools (dashboards for instance, Clua et al. 2005) and decision-making supports (Rice and Rochet 2005; Trenkel et al. 2007). These indicators are mostly related to fish communities and populations and intend to reflect fishing impact. On the other hand, indicators related to fishing activity, fleets and economics are seldom considered (but see Piet et al. 2007; Ceriola et al. 2008). However in order to understand management impacts on a fishery, particularly in the case of spatial management measures, spatially explicit bio-economic indicators of fleet and population dynamics are needed (Pelletier et al. 2008; Pomeroy et al. 2005). Within the pressure-state-response indicator framework (OECD 1993; Garcia and Staples 2000), it requires that fishing is no longer considered solely as a pressure but as a component of the fishery system that responds to the pressure of management. Fishing becomes the manageable link between regulation and biological response to management (Piet et al. 2007).

Metrics measure something specific, while indicators are supposed to tell us something different from what they actually measure (Daan 2005). Within the framework defined above, a metric is considered an indicator of management impact, if, and only if, it is sensitive to management and robust to uncertainties, in other words exclusive. To accurately assess these properties of the metric, the possible causes of variation in the metric value must be disentangled. Empirical data are often not available or are inadequate to perform this type of analysis, thus the relevance of an indicator is often based on conceptual models and experts' judgment. Formal evaluations of robustness to uncertainty are lacking (Fulton et al. 2005). Some authors have proposed the use of simulation in order to study metric properties and their future evolution under various management scenarios (Fulton et al. 2005; Livingston et al. 2005; Travers et al. 2006; Pelletier et al. 2008). This approach requires an operational model to be considered as the "real world". Its outputs are used for metric computations as if they were real world observations. The approach requires that the model be credible, i.e. that it has been validated, and that it provides metrics at a relevant scale. If these requirement are met, the simulation-based approach is the only way to permit replication, particularly regarding environmental conditions, and to allow statistical properties of the metrics to be investigated, for instance by using sensitivity analysis. Additional advantages in comparison to data collection in the field are the perfect knowledge at each time step of the modeled system (i.e. no observation error) and the limited cost of metric computation.

We apply a methodology relying on such a simulation based approach and sensitivity analyses to identify which metrics can be used as fishery management indicators. The goal of the study is twofold: first assessing management measure impacts on a wide range of metrics and second identifying indicators, by evaluating the relative sensitivity of the metrics to management measures compared to other sources of variation.

The approach is illustrated with the case of the pelagic fishery of the Bay of Biscay modeled with the ISIS-Fish software; however the methods used here are believed to be transposable to any other case study and model which has been carefully validated. The Bay of Biscay pelagic fishery is a multi-species, seasonal fishery involving French and Spanish fleets (Uriarte et al. 1996). It has suffered a crisis since 2005 when fishing for anchovy, the major target species of the fishery, was banned. The large variability in recruitment is known to affect the sustainability of this fishery (Lehuta et al. 2013) and spatial management measures have been proposed as a complementary tool to quotas to secure the sustainability of the fishery (ICES 1999). Given the multi-species aspect of the fishery, there are concerns that stricter management of anchovy leads to a report of the fishing effort on the other target species of the fishery, sardine, tuna, and sea bass with possible negative impacts on these alternative species. Lehuta et al. (2013) developed a spatial model of the anchovy population and fishery using the ISIS-Fish modeling framework and validated model behavior. Lehuta et al. (2010) tested the impact of a MPA on anchovy biomass and catch. The present study uses an improved version of the model, encompassing the four species and major economic processes, to investigate the effects of various management strategies, including MPAs, on a wide range of ecological and economic metrics representative of the whole fishery.

Material and Methods

Simulation-based approach

The methodology relies then on 2 steps. Firstly, metrics related to fish populations and fleets, which have been proposed to monitor fishery's dynamics, are reviewed. One or several aggregation levels (area, age-class, time step, and fleet) are associated with each metric. Two categories of metric are distinguished: the first category, referred to as 'management performance indicators' (P), consists of indicators which reflect long term performance of management and reflect management objectives through identified reference points or desired directions. The second category, called 'operational metrics' (O), consists of metrics that could potentially be computed and monitored annually to reflect the status of the fishery but do not have established reference points.

Secondly, the operational model is run according to an optimized simulation design, which incorporates multiple uncertainties identified in the system dynamics and the management rules. This allowed for:

- first, classical uncertainty analysis to be performed on 'management performance metrics'. This was to assess the ability to reach the management objectives and robustness to uncertainty.
- second, sensitivity indices for each metric ('performance' and 'operational') to be computed. These indices are used to extend classical MSE objectives and:
    - establish sensitivity and exclusivity of the metrics and their relevance as indicators of management impact
    - identify major sources of variations when performance metrics are not robust
    - identify operational metrics which are useful to complete the diagnostic of management impact in particular to understand the reasons for management failure to reach objectives

The approach considers that some prerequisites of management strategy evaluation are defined and available. In particular, we need:

1) a flexible operational model to simulate the fishery dynamics according to several assumptions of fishery parameterization and several management strategies. In this approach we used the ISIS-Fish model (Pelletier et al. 2009) parameterized and validated for the pelagic fishery in the Bay of Biscay (Lehuta et al., 2013).
2) the characterization of gaps in knowledge or uncertainties regarding the Bay of Biscay pelagic fishery which translate into uncertainties in model parameters.
3) the list of management strategies with explicit management objectives that should be assessed

Operational model: ISIS-Fish model of the pelagic fishery of the Bay of Biscay

The ISIS-Fish simulation tool was used to model the dynamics of the Bay of Biscay pelagic fishery (Lehuta et al. 2010; Lehuta et al. 2013). The simulation model is spatially explicit, time discrete (monthly time-step) and enables the modeling of fish populations, fishing activity and management dynamics through three interacting sub-models. The biological model includes a detailed and spatially explicit description of anchovy dynamics, consisting of 15 population stages (larvae to adults), which grow, migrate, reproduce, recruit and die according to stock specific parameters (Lehuta et al. 2013). It is completed with global surplus production models for four populations also targeted by the fleets: sardine (*Sardina pilchardus*), tuna (*Thunnus alalunga*), and two populations of sea bass (*Dicentrarchus labrax*) for the Channel and the Bay of Biscay (Vermard et al. 2012). A fishing behavior model (Random Utility model (RUM)) enables the monthly prediction of the allocation of fishing time on areas and métiers for French fleets based on a combination of fishing habits (historical distribution of fishing time), revenues in the previous time step (month) and a proxy of fuel costs for the activity, computed as the distance to the fishing area times the price of fuel (Vermard et al. 2008; Vermard et al. 2012). The average pattern of fishing time for the period 2000-2004 is assumed for the Spanish fleet and decision rules are used to reallocate effort depending on management constraints for this fleet (see *Management scenarios*). Fish prices are dynamically computed as a function of landed volumes (Vermard et al. 2012). Fuel costs are derived from fishing effort, fishing areas and fuel price (Vermard et al. 2012). No technical interactions exist between species because of differences in mesh size and fishermen's ability to recognize species from fish schools.

Figure 1 illustrates how the three sub-models interact to compute the distribution of fishing time and derive fishing mortality. At each time step, management rules are updated (catch left to TAC, areas closed, etc) and the métiers impacted by management identified. Combining the updated values of explanatory variables for the RUM and the information on métiers impacted by management, the behavioral model predicts the distribution of the fishing time of each fleet on its possible métiers. The fishing time of a métier applied to a fish population in a zone is proportional to the surface of the métier zone which overlaps the population zone. This fishing time is then standardized between métiers using the catchability parameters of the métiers. Fishing mortality for the population in the zone is finally computed using the accessibility of the population.

The model was validated with data of the period 2000-2004 (Lehuta et al. 2013, Vermard et al. 2012). The database of the model can be freely downloaded (Pelagic fishery of the Bay of Biscay, http://www.isis-fish.org/download.html). Model outputs are time series of state variables (biomass, effort, catch, revenues, etc) simulated for each population, fleet and area modeled (Figure 2).

Uncertainty hypotheses

Sensitivity analyses, carried out on the model at various stages of its development (Lehuta 2010; Lehuta et al. 2010; Lehuta et al. 2013), identified parameters which significantly affect model predictions (Table 1): anchovy larval survival, growth and migration rates, accessibility of tuna to fishing, target factors (strength with which a métier targets a species) for sea bass, recruitment of sardine, amount of live bait catches of anchovy by Spanish fleets for tuna fishing (païta), effort level of the fleets, French fleet behavior, species prices and fuel prices. Among those parameters, we distinguish between uncertainty of parameter estimates (the parameter has a constant value but the value is uncertain due to measurement or assessment error) and uncertainty of parameter dynamics (the parameter represents a process prone to inter-annual variability and thus is a variable whose value should change every year but we do not know how). Uncertainty ranges are identified for the former (16 parameters) and alternative scenarios of evolution proposed for the latter.

In this case an exhaustive analysis of possible scenario trajectories through Monte Carlo sampling, as is usually done, was not conceivable given the model computational costs. Instead two contrasting trajectories were designed and their impacts on the results were assessed. For fuel price, assuming a steady value over the simulation period, or alternatively, a linear increase on the basis of the last decade trend can be seen as the two extreme situations possibly encountered in the future. Inter-annual variability in natural mortality and spatial distribution has been demonstrated to be a major driver of fishery dynamics (Lehuta et al. 2013). Due to a lack of information on this inter-annual variability it was not possible to predict most likely scenarios. Instead two contrasting trajectories were compared: $\mathbf{H_1}$, assuming constant values of larval mortality and distribution in spawning areas for the entire simulation; and $\mathbf{H_2}$, using the sequence of values of larval mortality and spatial distribution in spawning areas respectively estimated and observed between 2000 and 2009 (Lehuta et al.

2013). In this case, the intention is not to represent the whole range of uncertainty but rather to give indications on how inter-annual variability in parameter values would affect the performance of management. This last factor will enter the uncertainty analysis in a different manner (see *Simulation design*).

Management scenarios and management objectives

The anchovy fishery was closed from 2005 to 2010 due very low biomass estimates and a long term management plan is currently in development to prevent such a long closure and its dramatic economic consequences in the future. The plan includes provisions for a closure until the end of the management year (which runs from July to June the next year for the anchovy fishery) when estimated current annual biomass is below a threshold fixed at 24000 MT (STECF 2009). This constitutes our base case (scenario 0) and is systematically applied in our simulations. Two kinds of additional measures are proposed, namely Total Allowable Catch (TAC) and Marine Protected Areas (MPAs). The TAC is set mid-year with a harvest rule, "Rule E", defined by the Scientific, Technical and Economic Committee for Fisheries (STECF) and South Western Waters Regional Advisory Council (SWWRAC), establishing the annual TAC level (STECF 2009). Rule E sets a TAC of 7 000 MT from July to June the next year for an estimated biomass in June between 24 001 MT and the so-called precautionary biomass level (Bpa) of 33 000 MT. For biomass above Bpa, the TAC is set at a certain proportion (γ) of the current biomass level, up to a ceiling of 33 000 MT, which is the maximum catch level that has been historically recorded (STECF 2009). In our simulations, catch proportion (γ) is set at 40% following the advice of the SWWRAC rather than a rate of 30% supported by the STECF. According to historical catches, Spain is entitled to 90% of the TAC. However, a bilateral agreement between Spain and France arranged the transfer of a part of the Spanish quota to France, raising its quota to 40% of the TAC.

In addition, MPAs have been proposed since 1999 to help maintain the reproductive potential of the stock (ICES 1999). Here, three designs of MPA are compared. Their objectives are to diminish fishing pressure on juveniles concentrations and on adults during the reproduction: MPA1 consists in the closure of the area located to the west of the Gironde estuary (Figure 3 zone C) during the reproduction (April-August); MPA2 is a closure applied in the same period but concerns the areas off the coast of Landes (Figure 3 zones D and E); finally MPA3 establishes the permanent ban of fishing in the Gironde area taking account of the fact that juveniles concentrate there all year long. Previous studies demonstrated that MPAs alone are unlikely to be effective (Greenstreet et al. 2009; Moustakas et al. 2006). Consequently, in our simulations MPAs are coupled to an effort reduction arbitrarily set to 20%. The reaction of French fleets to area closures is dynamically computed by the behavioral model according to the economic and ecological context (Vermard et al, 2012). When the closure of the Landes area (MPA 2) is enforced, it is assumed that the Spanish fleet reallocates its effort on anchovy in the rest of the métier zone still opened to fishing. No decision is required when closing Gironde (MPA1, MPA3) since the Spanish fleet does not fish anchovy in this area. MPAs are either combined with Rule E (scenario 2, 3, 4) or not (scenario 5, 6, 7) which results in eight management strategies including the base case (Table 2).

To assess the long-term performance of management scenarios, simulations are run for ten years from 2008 onward.

Management performance metrics (P) and Operational metrics (O)

Management objectives for the pelagic fishery are gathered from the anchovy long-term plan proposal (STECF 2009) and the requirements for the Good Ecological Status (GES) of exploited fish populations as defined in the Marine Strategy Framework Directive (Cardoso et al. 2010). The qualitative objectives are to secure relatively high yields from exploitation of the anchovy stock and guaranteeing the stability of the fishery while maintaining a low risk of stock collapse (STECF 2009). Performance metrics (P_1 to P_6) with corresponding reference points (targets or limits) or directions are derived from those management objectives:

- P_1: Number of years when biomass is above $B_{\mathbf{lim}}$ (21 000 MT). P_1 must be equal to the number of years of simulation.

- P_2: Number of years of fishery opening. P_2 must be above 90% of simulation duration (10% frequency of closure).

- P_3: Number of years with catch of anchovy higher than 7000 MT which is the threshold of economic profitability expressed by the sector (SWRAC 2008). P_3 must be equal to the number of years of simulation.

- P_4: linear trend in SSB. P_4 should show no degradation to guarantee reproductive capacity, and should thus be positive or null.

- P_5: Inter-annual variability (expressed by the normalized standard deviation) in landings. P_5 should be as close to zero as possible as a proxy of fishery stability, to guarantee continuous supply to the industry.

- P_6: Inter-annual variability in the proportion of the total population represented by recruits (expressed by the normalized standard deviation). The health of the stock has been defined as being proportional to the numbers of larger, older fish (Cardoso et al. 2010). For a short-lived species such as anchovy, however, age structure mainly reflects recruitment success and neither a reference point nor a reference direction exist. We thus considered stability of this structure as positive for population health and recorded the standard deviation of the proportion of recruits in the population, with a low variability being preferable for stock health.

We expect management measures to have significant benefits and to take the fishery closer to these objectives in comparison to the base case simulation. The values of the indicators are thus also compared with the values obtained in the base case simulation.

The primary objective of analyzing metrics other than performance metrics is to complete the diagnostic with metrics which reflect the effect of management on other features of the target population (such as spatial structure), as well as on the other populations involved in the fishery and on the activity and profitability of fleets. It also aims at identifying relevant indicators of management impact on fishery dynamics that are currently not used.

A list of candidate metrics that could help completing the diagnostic on management impact was identified from the literature. Among the metrics listed by Lehuta (2010 (Annex1)), those which are computable by the model are sorted and computed at several spatial and temporal scales:, for each of the five populations; for each life stage or age group for anchovy; by country; and by fleet (Tables 3 to 8). Given that there was neither a behavioral model nor economic information on Spanish fleets, economic metrics relate only to French fleets. In some cases, management is expected to influence the metrics in a given direction. When documented those expected effects are indicated in tables 3 to 8.

Operational metrics are computed yearly, either as the sum, average or extreme of monthly values (species prices $O_{47\text{-}50}$, revenues $O_{35\text{-}38}$) or at a particular month (spatial distribution of anchovy in spawning areas O_7, proportion of juveniles in the population O_2). Biomass and spawning intensity per area as well as effort per métier are multidimensional metrics that are transformed into uni-dimensional metrics using a PCA (table 3 and 5, $O_{7,8,22\text{-}26}$). The first axis of PCA and possibly the second when it represented a large amount of variability were used as metrics and the correlation of axis with descriptors guided the interpretation of these composite metrics. Temporal trends in the annual values of the metrics are searched through linear and log-linear model adjustment ($O_{14-17,39-42,55-58,63-66}$). Non-significant slopes were set to zero. Standard deviation in the time series (de-trended time series when a trend was identified) expresses the annual variability/stability of the metric value ($O_{1,18-21,43-46,49,50}$).

Simulation design and investigation of metric properties

The objectives of the paper are twofold: Firstly we carry out a classical management strategy evaluation based on the set of "performance" metrics and accounting for uncertainties. Secondly we propose to explore the sensitivity and robustness properties of performance and operational metrics by computing the sensitivity indices associated with uncertainties and management measures. Both objectives require building and running the simulations according to a statistical simulation design, which includes both management rules and uncertainty sources as factors to allow a comparison of their respective effects and their interactions on the metrics. For a given simulation, a set of values for the uncertain parameters and a management strategy are selected. The simulation design was built sequentially. Firstly, a factorial fractional design (FFD) of resolution V is created for uncertainty sources. It is an optimized design appropriate to compute sensitivity indices for the factors and their first order interactions based on a model of variance decomposition (Box et al. 2005). It consists of an algebraically chosen subset (fraction) of a full factorial design (the full factorial design allows for the estimation of interactions at all orders). In such a design, each factor can take a discrete number of values (modalities), which we chose equal to 2, assuming a linear relationship between factors and outputs. We defined the modalities as being either the extreme values of the uncertainty range or alternative hypotheses on their inter-annual variations (Table 1). The fractional design concerns 17 parameters (256 simulations). Second, to allow for comparison between management measures and between hypotheses H1/H2 of larval mortality and spatial distribution in the uncertainty analysis, this design was replicated for each of the two hypotheses H1 and H2 and each of the eight management scenarios (256*2*8 = 4096 simulations).

The management strategy evaluation is done on multivariate objectives by comparing the average values of the six performance metrics across management scenarios using radar plots (Garcia and Staples 2000). To allow for an easier reading of the plot, the outer end of the radials represent the management objective (P_1 to P_3) or the desirable direction (P_4 to P_6).

The sensitivity of performance (P) and operational metrics (O) to management measures and their robustness to uncertainty are then investigated. Firstly the values of performance and operational metrics are compared across scenarios using boxplots showing the median and 0.25/0.75 quartiles. The hypothesis tested is $M_{sc.} = M_0$ where $M_{sc.}$ denotes the average value of the metric in simulations with management scenario sc, sc $\in$ [1,7] and M_0 is the value of the metric in the base case scenario. The significance of the effect of one scenario compared to another is also evaluated ($M_{sc.i} = M_{sc.j}$, with $i \neq j$). The direction and significance of the effect of each management scenario compared to the base case is reported in tables 3 to 8 for each operational metric. An ANOVA is then performed with management scenarios and uncertain parameters as explanatory variables. The results of the ANOVA are used to compute sensitivity indices for the metric and to identify the major sources of variation (Saltelli et al. 2000).

Results

The results are first examined to evaluate management strategies. Performance metrics display different responses to the management scenarios (Figure 4). In terms of management objectives, only metric P_1 and P_4 show average values close to or above the objective (i.e. anchovy biomass above B_{lim} more than 7 years for P_1 and positive values for P_4). P_2, the number of open fishery years, averages around 7 in scenarios with TAC and around 5 in scenarios with only MPAs and for the base case; thus in these last cases, the fishery is closed half the time. Finally, anchovy catches, P_3, exceed the economic threshold on average only twice in 10 years with a maximum of three years in the base case. If the performances are globally low, particularly from an economic point of view, some scenarios perform better than others and, with the exception of metric P_3, there is good consistency in the ranking of scenarios across performance metrics. These results demonstrate that scenarios coupling TAC with MPA1 or MPA3 are the most efficient and that the base case is the least efficient. The ranking is completely inverted for metric P_3 which represents an economic objective. P_1, P_2 and P_3 values, which represent final outcomes, are not sensitive to the MPA design and the metrics mostly reflect the presence or absence of a TAC. P_4 and P_5 however, which represent measures of the stability of the fishery over the period, show variations depending on the MPA design. MPA1 and MPA3 generally have a stabilizing effect on the fishery in comparison with MPA2. The variability of population structure P_6 averages around 29% of annual variation and is not influenced by management strategies.

The robustness of the evaluation of management performance to uncertainties is assessed using boxplots (Figure 5). The results must not be interpreted in terms of risk, because they only include extreme values of parameters (assuming uniform distribution and linear response) and two scenarios for inter-annual variability. They still provide information on the range of possible values resulting from the combination of uncertainties. Most metrics show very large uncertainty intervals, and significant effects of management can only be detected on metrics P_1, P_2, P_4 and P_5. Even in the worst simulations, scenario 4 remains the most efficient of the considered scenarios and limits negative impacts on the population (P_1=7, P_4=-4%). On the other hand, none of the scenarios can prevent severe negative economic impacts (P_3=0 and P_5=111%). Comparing the two scenarios of inter-annual variability H1/H2, we demonstrate that H2 (variable larvae survival and migrations) always results in more pessimistic predictions (Figure 5). However, the ranking of management strategies is unchanged, and thus still supports decision-making and choices between management strategies.

Sensitivity indices permit further explanation of the limited effects of management by breaking down the uncertainty reflected by the boxplots. They indicate the primary source of variation that metrics are responding to (Table 9, Figure 6). As expected performance metrics related to the stability of the population, such as P_6 and P_4, are more sensitive to inter-annual variability in anchovy life history traits than to management measures (Figure 5, Table 9). P_1 is primarily influenced by the hypotheses regarding inter-annual variability and secondarily by management measures. This demonstrates that an appropriate management strategy can help counter the negative effects of unfavorable or unstable environmental conditions (Table 9). The other performance metrics are sensitive to management and parameters related to fishing activity such as effort and amount of anchovy bait fished (païta) (P_2, P_3, P_5) (Table 9). P_5 responds strongly to management measures and interactions with other parameters such as effort (effp1), anchovy bait catch (paita) and price (spPrice) are significant (Figure 6). It reveals that the effect of management strategies could be amplified or attenuated depending on the values for those parameters.

Among the 66 metrics investigated, only 9 are primarily sensitive to management: the percentage of immature anchovy in the catch (O_6), the final biomasses of tuna (O_{11}) and sea bass (O_{12}, O_{13}), the metrics describing effort distribution among métiers for trawlers profil1 (O_{22}, O_{23}) and purse seiners from the Basque Country (O_{26}), total anchovy landings (O_{28}) and Spanish landings (O_{30}). Metrics relating to anchovy population mainly reflect inter-annual variability in larval survival and migrations (Table 3). Economic variables like revenues and fuel dependency are highly uncertain and dependent on assumptions on effort, species prices and fuel price evolution; the effect of management is comparatively low (Tables 6, 7, 8). On the contrary, management decisions influence the 9 variables listed above regardless of environmental or economic forcing and thus they are reliable indicators of management measures impact. In addition, analysis of these variables can help to provide insights into the mechanisms underlying management performance.

Management scenarios in particular are the most influential drivers of effort distribution for the trawler fleet Profile 1 (most dependent on anchovy). This effort distribution is represented by metrics O_{22} and O_{23} which are the first and second axes of the PCA on effort per métier. They represent respectively the proportion of total effort spent on métiers targeting anchovy relative to other species and the proportion of effort spent on anchovy in the Gironde area relative to other zones. The metric O_{22} shows that MPA scenarios (5, 6, and 7) do not modify the amount of effort on anchovy métiers compared to the base case, while scenarios involving TAC (1, 2, 3, 4) decrease this effort significantly (Figure 7A). Sensitivity indices (Figure 7B and 7D) confirm the significant effect of scenarios 1,2,3,4 on the value of O_{22} as well as the influence of the global level of effort on the metric. They also show that species prices influence the choice of the target species in scenarios involving TAC (interaction effp1:TAC-MPA2, effp1:TAC-MPA2, etc.). Metric O_{23} shows that in every scenario, the effort is spatially displaced when compared to the base case, with a reduction of effort in the Gironde area which was the goal of MPA designs 1 and 3 (Figure 7C). O_{23} is mostly sensitive to scenario 7 (MPA3) which significantly reduces the effort in Gironde and secondarily to scenarios 1 (TAC) and 4 (TAC coupled with MPA3). However, sensitivity indices show that the amplitude of this effect is dependent on species price (interactions priceSp:TAC, priceSp:MPA3).

These metrics enable an explanation of the relative failure of MPAs according to the performance metrics. Firstly, it shows that MPA1 and MPA3 actually reduce effort in the area Gironde. However, with constant global effort, the effort originally exerted there is reported on métiers also targeting anchovy but in other areas, which maintains a high pressure on the stock. On the other hand, TAC, even when not associated with MPAs in the Gironde, reduced effort in this area when compared to the base case (Figure 7C). Furthermore a limiting TAC closes the fishery before the end of the management year, i.e. before the spawning season, when the Gironde area is usually harvested. This explains the relatively minimal performance gain when TACs are coupled with MPAs. In conclusion, these two metrics in combination with species prices and total effort could be monitored or controlled to assess management efficiency.

Metrics O_{28}, O_{29}, O_{30} monitor international landings and landings by country over the simulation period. They are mostly sensitive to uncertainty on païta catches (not landed), stressing the importance of better monitoring of this activity to lower the uncertainty around the metrics and to help improve yield. All three metrics are also sensitive to the level of fishing effort in the Spanish fleet and main French fleets, which demonstrate the influence of the competition between fleets on catches (Table 5). Finally management measures also significantly impacts on catch levels (O_{28}) and the distribution of catches between France and Spain (O_{30}). With the exception of scenario 1 (TAC), the global catch level is lower in the presence of regulation than in the base case (significant difference for scenarios 3, 5, 6, 7).

However metrics by country reveal contrasting situations. Catches of Spanish fleets are systematically higher than in the base case when a TAC is enforced; while catches by French fleets are lower in all scenarios. Actually Spanish quota is rarely reached in simulations, while French quota is always very limiting.

The percentage of immature anchovy in the catch O_6 has been proposed as an indicator of fishing intensity by Rochet and Trenkel (2003) to monitor the ability of fish to reproduce at least once. We expected to see a reduction of these catch of small anchovies in scenarios involving the protection of the Gironde area in winter and autumn when juveniles are concentrated there. The results show that all of the proposed scenarios, and particularly the scenario involving MPA3, achieve better protection of the juveniles than the base case. This can be related to the previous evidence that all scenarios reduce fishing pressure in the Gironde area, proving the appropriateness of management to achieve this objective. However, although significant, the variation in values is actually very small (2.5% of juveniles in catch in the base case, 1% with scenario 4) and it is questionable if such a small difference can explain the improvement in population health highlighted by performance metrics. The sensitivity indices also show that the metric is sensitive to the hypotheses on natural mortality and migration.

Finally management measures designed to protect anchovy also affect tuna and sea bass (O_{11}, O_{12}, O_{13}) while sardine biomass (O_{10}) is mostly influenced by sardine recruitment (Table 4). Tuna and sea bass biomasses are primarily sensitive to the effort deployed by the trawlers. However, they show significant variations with management, more specifically a decrease in final biomass of sea bass with a TAC, and significant increases for both species with all other management measures (Table 4). These results are unexpected as reinforcing management constraints on anchovy was assumed to create increased pressure on other target species. Because sensitivity indices showed sensitivity to effort levels, it is thought that the positive effect doesn't come from the MPA itself but rather from the effort reduction associated with MPAs. This diminution of global effort likely compensates for the increased proportion of time spent on the métiers targeting these species.

This metric analysis provides a detailed assessment of the effect of management measures on the fishery both in terms of performance and understanding of underlying mechanisms.

Discussion

We have designed a framework to assess the properties of fishery metrics and to evaluate their relevance as indicators of management impact. The simulation design allows for the evaluation of the robustness of management actions to uncertainties, both regarding unpredictable future conditions and poorly understood processes. It also allows sensitivity indices to be computed and used to measure sensitivity of the metrics and to conclude on exclusivity. Although the properties of the metrics analyzed here are specific to the case study, the methodology is transferable to other models and ecosystems. For instance, a comparison with the indicators selected through our method for a flatfish fishery would be of great interest. The approach could also be extended to identify indicators of other pressures (environmental conditions, fishing, decision process, etc.) providing an appropriate simulation design.

Our first step consisted in translating management goals expressed by various institutions (ICES, STECF (2009), Common Fisheries Policy, Marine Strategy (Cardoso et al.

2010), and the industry through the SWRAC) into metrics to measure the level of achievement of management objectives by the proposed management strategies. For most of the identified management objectives, metrics and goal values (reference points) although not explicitly identified by management institutions, were straightforward (such as P1 to P4 which are based on reference points). For the objectives linked to fishery stability (P5 and P6), we chose normalized standard deviations and specified the desirable direction of change as no reference points were available. This step alerted us to the low number of quantitative objectives actually expressed regarding the anchovy fishery. More generally, moving from qualitative objectives to quantitative indicators is a delicate task.

The use of a process model, explicitly describing the mechanisms, overcomes major issues regarding the accessibility of information for the evaluation of indicator properties. It allows for the consideration of a wide range of metrics: in particular those related to the economic situation of the fleets; anchovy demographics and spatial structure; and the health of the other target species of the fishery, which meets the requirements of an ecosystem approach to fishery (Jennings 2005). For this purpose, the model developed by Lehuta et al. (2010) to evaluate the impact of management on anchovy biomass and catch has been improved by the addition of a fishing behavior model including economic variables, and the dynamics of the other major target species of the fishery. These aspects are usually not considered in management strategy evaluation because they either cannot be simulated by the models or because the data needed are difficult or expensive to collect empirically (as for spatially disaggregated metrics). In particular, an investigation of the impact of management scenarios on economic sustainability of the fleets is rarely done because the economic data are usually inaccessible (often confidential) and it requires explicit modeling of fishers' behavior (Holland, 2000, Ulrich et al., 2002, Holland, 2003, Kraak et al.,2008 and Bastardie et al., 2010).

Another difficulty lies in the synthesis of the information provided by such a large number of metrics. Since the model is spatialized and dynamic with a monthly time step, metrics were intrinsically multidimensional and methods to systematically explore the various aggregation levels were looked for. As previously done by Drouineau et al. (2006) we used PCA to summarize spatially disaggregated information, but Shanon-Wiener indices proposed by Marchal et al. (2001) and Partial Least Square regression (Tenenhaus et al. 1995; Lehuta et al. 2010) could also be used. In a context where spatial resolution is higher, Woillez et al. (2009) also proposed several descriptors of fish distribution. These composite indices are however not directly observable and are therefore unsuitable for monitoring. Nevertheless, we confirmed the need for several aggregation levels, previously stressed by Travers et al. (2006), especially when spatial disaggregation is concerned. For instance, we demonstrated the benefit of collecting spatially disaggregated effort data to monitor the impact of spatial and even non-spatial management measures. Indeed, TAC, when constraining, appeared as an “implicitly spatial measure” (Babcock et al. 2005) that provided protection to zones that were exploited at the end of the management year.

Regarding temporal aspects, values of the metrics at the end of the simulations were examined as proxies for long-term performance. Time series were also synthesized by linear trends or values cumulated over time (revenues). Several authors promote the use of indicator trends rather than absolute values to smooth the signal and to avoid alerts due to high inter-annual variability (Trenkel et al. 2007). However in our case, trends presented the same sensitivity to inter-annual variability as did point-in-time values.

The simulations were used to produce two kinds of answers: i) the classical evaluation of management strategies against their objectives, against each other, and the evaluation of their robustness; and ii) the evaluation of the appropriateness of metrics to assess management strategies through the study of sensitivity indices.

Regarding MSE, we showed that most management objectives are unlikely to be reached by the strategies implemented. The exception is the growth rate of the population whose average values are positive. The ranking of the management strategies according to their ability to approach management objectives showed the necessary trade-off between biological and economic goals. The results suggested that scenario 2 (TAC combined with an MPA on area Gironde during spawning) is the most efficient regarding all objectives but one (P3). Scenario 1 (TAC), which is the current regulation, was almost as efficient as it maintained reasonable performances on biological objectives (P1: Blim, P4: population growth, P6: age structure stability) but ensured better results on economic objective (P3: catch level). MPAs on the other hand did not perform much better than the base case.

The model allows the extension of the diagnostic to other species. Significant impacts of management measures designed for anchovy were highlighted on the population growth rate of sea bass. Despite the poorly described dynamics for this species, simulations clearly show a negative effect of TACs set for anchovy. Sea bass actually represents the most profitable alternative to anchovy and fishers report their effort on it when anchovy quota is exhausted. However those negative effects do not occur if TAC is coupled with MPA and effort reduction. This supports the adoption of scenario 2 rather than scenario 1.

Beyond average values, the uncertainty analysis informs on the robustness of the conclusions to uncertainties. We considered management strategies as factors of the uncertainty analysis. Thus the comparison between strategies was possible including an evaluation of the significance of the differences between their average performance values.

The kind of uncertainty analysis we used does not provide results in term of risks for management to fail, because the distribution of uncertain parameters is assumed to be uniform and because H_1/H_2 are not an exhaustive representation of uncertainty in mortality and migration. This approach rather brackets uncertainty. Here, confidence intervals reflect extreme consequences of a strategy accounting for a wide range of interacting uncertainty sources. Within a scenario of mortality and migration (H_1/H_2), it thus corresponds to a strict application of the precautionary approach. Here the uncertainty analysis confirmed that scenario 2 is not only the most efficient but also the most cautious since extreme values obtained stay acceptable regarding objectives. Moreover even if the accuracy of simulated absolute values can be questioned, this approach provides a ranking of management strategies relative to each other, and in our case, showed that this ranking was robust to uncertainty.

The simulations were then used to compute sensitivity indices for both performance metrics and operational metrics and to conclude on the metrics' appropriateness as indicators of management impact.

Sensitivity indices allow for the evaluation of metrics regarding two of the criteria that make them indicators: sensitivity and exclusivity (Rochet and Trenkel 2003). The sensitivity index related to management precisely measures sensitivity in the sense of Rochet and Trenkel (2003), i.e. ability to respond to the pressure under study (in this case management measures). The other sensitivity indices reflect robustness to uncertainties and if negligible, show the exclusivity of the indicator to management. Regarding performance metrics, we showed that management decisions should rather be based on metrics P1 (frequency above Blim), P2 (frequency of fishery openings), P3 (catch level), P5 (stability of catch), because the advice based on P4 (trend in biomass) and P6 (variability of age structure) largely depends on uncertain processes and future conditions met by the fishery; in other words: P4 and P6 do not meet the exclusivity criteria.

Furthermore, we identified new metrics sensitive and even exclusive to management, which are useful to understand the changes induced by management implementation. Operational metrics ($O_{6,11\text{-}13,22\text{-}23,26,28,30,45}$) were sensitive to management and offered insight in the mechanisms underlying management actions. Particularly the study of fishing effort distribution among areas and métiers showed that the considered scenarios, even when they failed to reach management objectives, are actually efficient in reducing the pressure on the Gironde area and in reducing the catch of juvenile anchovy, which were implicit objectives of management. However, when MPAs are not coupled to TACs, the effort is reported on anchovy in other areas rather than on other species, providing an explanation for low benefits of MPAs.

If an indicator is more sensitive to an uncertainty source than it is to management actions, it indicates that the value of the indicator cannot be accurately predicted by the model until the uncertainty is reduced. The direction of the impact of management measures on its value may still be evidenced but is unlikely to be significant. Furthermore, significant interactions between management and parameters indicate synergies or antagonisms. This means that the expected impact of management actions on the indicator value may not only be biased but that the direction of the impact could also be the opposite. Consequently, the simulated value of the indicator cannot be trusted.

These significant interactions also warn us about our possible inability to interpret the metric variations measured in the field, if the uncertainty source cannot also be precisely measured.

It is important to make a distinction here between different kinds of uncertainty in order to correctly interpret sensitivity indices. We differentiate metrics sensitive to uncertain knowledge from metrics sensitive to uncertain future conditions. In the first case, the sensitivity indices inform on the necessity to improve knowledge to allow robust assessment using the model and correct interpretation of metric values measured on the field. In MSE, uncertainty analyses are often limited to few processes (usually recruitment) and few parameters (catchability, weight at age). Here we evidence the risk of disregarding other uncertainty sources; in particular risk of failure could be underestimated. Population growth rate for instance was influenced by the hypotheses made on the effort of the Spanish fleet and the level of catches for païta that are usually not explicitly accounted for. "Operational metrics" were also mostly sensitive to uncertainty due to lack of knowledge about the fishery because they represent finer processes and more local scales on which knowledge is more uncertain, typically economic processes (prices). The sensitivity analysis thus helps in identifying needs and priorities in data collection.

The second case concerns the uncertainty of processes which vary from year to year, possibly under the pressure of environment. In these cases, sensitivity indicates that the impact of the management strategy depends on the conditions met, which are usually unpredictable. This is the case for performance metrics P_4 (growth rate) and P_6 (inter-annual variability of recruits) and for most of the operational metrics related to anchovy population dynamics, spatial and demographic structure. Shin et al. (2005), Greenstreet and Rogers (2006) and Travers et al. (2006) already pointed out the sensitivity of age structure and metrics related to size to environmental variability. These indicators are typically inadequate to monitor the impact of management. For instance, it is often considered that high population growth rate (P_4) is a sign of population health and is implicitly attributed to efficient management. In the case of anchovy, sensitivity indices indicate however that a high population growth rate value most likely results from a combination of favorable environmental and/or economic conditions rather than from efficient management. Conversely no management strategy can overcome adverse conditions. If the relationship between the metrics and the forcing is resolved, it is possible to use the metric in combination with indicators of the current condition of the system. For instance population growth rate could be interpreted in terms of management impact if an index of larval survival was available. Reference points could then be conditioned to the value of the larval survival index. An approach for the identification of reference point and the combination of variables was proposed by Link et al. (2002) using multivariate analysis such as PCA.

Finally we also found that the information provided by sensitivity indices was directly interpretable in proposing new management actions.

As previously discussed growth rate was more sensitive to effort level and païta than to the management measures evaluated. Most performance metrics were actually sensitive to these two parameters, which are uncertain but manageable factors. Regulation of effort or control of païta catches thus appear as potentially efficient management actions. This is relevant to ongoing discussions about the necessity to include live bait catches of anchovy in the TAC (SWRAC 2009).

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Figure captions:

Figure 1: Graphical summary of the ISIS-Fish model of the pelagic fishery in the Bay of Biscay. The chart represents the events simulated by each sub-model (biology, exploitation and management) at each time step (t, month) and the connections between them which result in the computation of the fishing mortality (*F*). Bolded words represent processes; italic is used to indicate state variables dynamically computed. F: Fishing mortality; M: natural mortality; VPUE: Value landed per Unit of Effort.

Figure 2: Examples of time series of outputs produced by the ISIS-Fish model of the pelagic fishery in the Bay of Biscay. The average time series obtained in the base case simulation is plotted (continuous bold line) together with 95% confidence intervals derived from the simulation design. The dash line represents the average time series obtained in simulations with management strategy 2 (TAC +MPA 1). A. Monthly biomass of anchovy, with reference levels Blim (biomass limit) and Bpa (precautionary biomass). B. Monthly effort of trawlers profil 1 on métiers targeting sea bass in the Channel. C. Monthly catches of anchovy by trawlers profil 1 in area Gironde. D. Monthly revenues generated by French fleets.

Figure 3: Map of biological and management areas for anchovy in the Bay of Biscay. A North, B. Rochebonne, C. Gironde, D. Landes off, E. Landes coastal.

Figure 4: Radar plot of average value obtained in simulation for the performance metrics in each management scenarios. Performance metrics are ordered on the graph according to the dimension to which they referred: biological objectives on the right and economic objectives on the left. Metrics are scaled so that the more on the edge the better. The scale goes from 0 to 10 (simulation duration) for P_1 to P_3, from 0 to the maximum value observed in simulation for $P_{3.}$ We plot the inverse of P_5 and P_6 so that the values range from Infinity to the lowest value observed in simulation. P1: no. years with biomass higher than B_{lim} $\in$[0;10]; P2: no. years of open closure $\in$ [0;10]; P3: no. years with anchovy catch >7000t $\in$ [0,max=3.47]; P4: trend in biomass time series $\in$ [min;max]; P5: 1/inter-annual variation in anchovy landings $\in$ [Infinity;max]; P6: 1/variability of age structure $\in$ [Infinity;min]. “min” and “max” stands respectively for minimum and maximum obtained in simulations.

Figure 5: Boxplots of the values of the six performance metrics depending on management strategies (x axis) (boxes represent the median and first and third quartile). The solid square represents the average value obtained in simulations with constant natural mortality and migration scheme, while the open square is the average value in simulations including inter-annual variability in these processes.

Figure 6: Sensitivity indices (16 highest) corresponding to each uncertainty source and management scenario for metric P_4: Anchovy population growth rate and P_5: Variability of anchovy landings. Sensitivity indices relating to management are in black. ":" represents interaction between two factors. Please report to Table 1 for the meaning of the abbreviations.

Figure 7: Effect of management scenarios on the allocation of effort of trawlers profile 1 on métiers, metrics O_{22} (top) and O_{23} (bottom). A and C: Simulated values of the metric depending on management scenario (x axis) (boxes represent the median and first and third quartile). B and D:. Sensitivity indices (16 highest) of the metric corresponding to each uncertainty source and management scenario and computed based on variance decomposition; ":" represents interaction between two factors. Please report to Table 1 for the meaning of the abbreviations.

Table 1: The table present the list of uncertain parameters considered in the uncertainty analysis. It describes the role of the parameter in the model in the frst column and the two modalities (alternative values) considered and the rational for their choice with corresponding references in the second column.

Parameter (abbreviated name)	Description and modalities
Larval survival rate and spatial distribution of biomass in spawning areas (HypH)	- Hyp. H1: parameters are kept constant at the average assessed/observed value on the period 2000-2009 - Hyp. H2: sequence of values assessed/observed on the period 2000-2009 (Lehuta et al., 2013)
Anchovy growth curve (gro)	The uncertainty interval for the K parameter of the Von Bertalanffy growth curve is unknown. Extreme values for K are assessed by hindcast simulations, assuming that: - The minimum is the lowest value allowing the simulated population to increase without fishing - The maximum is the highest value, with which the simulated population decrease with fishing levels of 2000-2004
Accessibility of tuna in autumn (corresponds to the biological part of catchability) (Qt)	+/-20% of estimated value ($6.76e^{-5}$) (Lehuta, 2010)
Target factors (intensity of search of a métier on a species) for Channel sea bass in December-January (Tbc)	Bounds of the confidence intervals of the estimates (Lehuta, 2010, Annex 3).
Target factors (intensity of search of a métier on a species) for Biscay sea bass in April-May (Tbb)	Bounds of the confidence intervals of the estimates (Lehuta, 2010, Annex 3).
Sardine recruitment (numbers) (Rsar)	Two alternatives values ($3.3e^{9}$; $1.6e^{9}$) corresponding to the average five best, and

	respectively worst recruitments observed by acoustic surveys between 2000 and 2009 (ICES, 2009).
Live bait "païta" catches (paita)	- Harvest of 2 MT per month and vessel (A. Uriarte, pers. Comm.) - No catches at all.
Fishing time per month for each of five fleets (effp1,effp2,effb1,effb2,effsp)	Minimum and maximal monthly effort observed between 2000 and 2004 (based on logbook data). (Lehuta et al., 2013)
Weight given to opportunistic vs. traditional behavior of French fleets (coefRump1, coefRump2, coefRumb1, coefRumb2)	Confidence intervals for the Random Utility Models estimates relating to profitability and habits. (Vermard et al. 2012).
Average annual fuel price (priceGas)	2 hypotheses : - constant value equal to the fuel price in 2008 (0.59 €.L^{-1}) - same linear trend as from 1996 to 2008 (3% annual increase)
Landings prices of the five populations (spPrice)	+/-20% variation of the flexibility coefficient. This determines the influence of landed volume on species price. (Vermard et al. 2012)

Table 2: Description of the management scenario tested in the study. The first column present to number used in the text to refer to the different scenarios, while the management measures enforced are described in the second column.

	Description of the management scenario (combination of management measures)
0	Base case : closure of anchovy fishery when biomass drop below B_{lim}[a]=21000MT
1	Base case + rule E: TAC=7000MT if 24000MT < biomass < 33000MT TAC = min(33000MT, γ biomass), γ=0.4
2	Base case + rule E + MPA[b]1: Gironde April to August + effort control (20% reduction)
3	Base case + rule E + MPA2: coast of Landes April to August + effort control (20% reduction)
4	Base case + rule E + MPA3: Gironde all year round + effort control (20% reduction)
5	Base case + MPA1 + effort control
6	Base case + MPA2 + effort control
7	Base case + MPA3 + effort control

[a] B_{lim}: Biomass limit

[b]MPA: Marine Protected Area

Table 3: Indicators related to the anchovy population and direction and significance of the effect of management scenarios on their value.

Management effect on anchovy population

	Indicator	Description and/or computation method	Reference	Expected effect[a]	Management effect[b] 1.TAC	2.TAC-MPA1	3.TAC-MPA2	4.TAC-MPA3	5.MPA1	6.MPA2	7.MPA3	Sensitivity
O1	Variability in population biomass	Standard deviation of detrended biomass time series	Rochet and Trenkel, 2003	-	+*	+*	+*	+*	-	+*	-	hypH
O2	Age structure	% of juveniles in the population in October	Cardoso et al., 2010,	+ due to protection of	-	-*	-*	-*	-*	-*	-*	hypH
O3	Age structure	% of recruits in the population in June	Pomeroy et al., 2005	spawners and recruits	-*	-*	-*	-*	-*	-*	-*	hypH
O4	Average length in the reserve	Average length in June in area Gironde, proxy of growth speed and age structure	Babcock et al., 1999; Amand et al., 2004	- due to protection of recruits	+	+	+*	+*	+	+	+	Gro
O5	Average length in the reserve	Average length in June in area Landes, proxy of growth speed and age structure	Babcock et al., 1999; Amand et al., 2004	+ due to protection of adults	-	-	-	-	-	-	-	hypH
O6	% immature in the catch	Cumulated catches from recruitment to first spawning	Rochet et Trenkel, 2003	- due to protection of juveniles with MPA3	-*	-*	-*	-*	-	-	-*	MgtStr
O7	Spatial	Scores on axis 1 of a PCA	Amand et	MPAs are	-*	-*	-*	-*	-*	-*	-*	hypH

	distribution in spawning areas in June	on % of biomass per area : axis 1 opposes biomass in areas Landes off and North (negative side) and Rochebonne (positive side)	al., 2004	supposed to enhance biomass in the protected area								
O8	Spatial distribution of spawning	Percent of eggs hatching in each area analyzes by a PCA, axis 1 opposes areas Landes off and Gironde (negative side) and areas Rochebonne (positive side)			+	+	+	+*	+	+	+	hypH
O9	Spawning distribution in time	% of egg spawned before July			+	+	+	+	+	+	+	effsp

[a] When described in the literature, expected direction of change in the value of the metric due to management strategies.

[b] Direction of the effect of each management strategy on the metric compared to the base case (+ positive effect ; - negative effect). '*' indicates significance of the effect (pvalue <0.05).

[c] Main factors to which the metric is sensitive: hypH: hypotheses on inter-annual variability of survival of larvae and migration; Gro: anchovy growth curve; MgtStr: management strategies; effsp: effort level of Spanish fleets.

Table 4: Indicators related to the other target populations and direction and significance of the effect of management scenarios on their value.

	Indicator	Description, computation method and expected effect[a]	Reference	Management effect[b] 1.TAC	2.TAC-MPA1	3.TAC-MPA2	4.TAC-MPA3	5.MPA1	6.MPA2	7.MPA3	Sensitivity[c]
Management effect on the other populations											
	Final biomass	Biomass at the end of the simulation									
O10	Sardine			+	+	+	+	+	+	+	RSar
O11	Tuna			+	+*	+*	+*	+*	+*	+*	effp1, MgtStr
O12	Bass Biscay			-*	+*	+*	+*	+*	+*	+*	effp1, MgtStr
O13	Bass Channel			-*	+*	+*	+*	+*	+*	+*	effp1, MgtStr
	Growth rate	Trend in log (biomass)	Rochet et Trenkel, 2003								
O14	Sardine			+	+	+	+	+	+	+	RSar
O15	Tuna			+*	+*	+*	+*	+*	+*	+*	effp1
O16	Bass Biscay			-*	+*	+*	+*	+*	+*	+*	effp1
O17	Bass Channel			-*	+*	+*	+*	+*	+*	+*	effp1

	Annual biomass variability	Standard deviation of the detrended time series of biomass	Rochet et Trenkel, 2003								
O18	Sardine			-	-	-	-	-	-	-	Rsar
O19	Tuna			+	+	+	+	-*	-*	-*	Gro, effp1, priceGas
O20	Bass Biscay			-*	+	+	+	+*	+*	+*	effp1
O21	Bass Channel			-	-*	-*	-*	-*	-*	-*	effp1, priceGas

[a] When described in the literature, expected direction of change in the value of the metric due to management strategies.

[b] Direction of the effect of each management strategy on the metric compared to the base case (+ positive effect ; - negative effect). '*' indicates significance of the effect (pvalue <0.05).

[c] Main factors to which the metric is sensitive: hypH: hypotheses on inter-annual variability of survival of larvae and migration; Rsar: sardine recruitment; effp1: effort level of pair trawlers profile 1; MgtStr: management strategies; Gro: anchovy growth curve; priceGas: scenarios of fuel price.

Table 5: Indicators related to fishing activity and direction and significance of the effect of management scenarios on their value.

Management effect on fishing activity

	Indicator	Description and/or computation method	Management effect[a]							Sensitivity[b]
			1.TAC	2.TAC-MPA1	3.TAC-MPA2	4.TAC-MPA3	5.MPA1	6.MPA2	7.MPA3	
O22	Effort distribution over métiers tr.p1[c]	Scores on 1st axis of a PCA : métiers targeting anchovy on the positive side	-*	-	-*	-*	+*	+	+	MgtStr
O23	Effort distribution over métiers tr.p1[c]	Scores on 2nd axis of a PCA : métier practice in Gironde on the negative side	+*	+*	+*	+*	+*	+*	+*	MgtStr
O24	Effort distribution over métiers tr.p2[c]	Scores on 1st axis of a PCA : métiers targeting sardine and anchovy on the positive side	-*	-*	-*	-*	+	-	-	spPrice
O25	Effort distribution over métiers tr.p2[c]	Scores on 1st axis of a PCA : métiers targeting sardine on the positive side and anchovy on the negative	+*	+	+*	+*	-*	+*	-	spPrice
O26	Effort distribution over métiers se.bc[c]	Scores on 1st axis of a PCA : métiers targeting anchovy on the negative side	+*	+*	+*	+*	-	+*	+*	MgtStr
O27	Effort distribution over métiers se.br[c]	Scores on 2nd axis of a PCA : métiers targeting anchovy on the negative side	+*	-*	-*	-*	-*	-*	-*	effb2
O28	Anchovy international landings	Landings cumulated over the simulation	+	-	-*	-	-*	-*	-*	Paita, MgtStr
O29	Anchovy landings of French fleets	Landings cumulated over the simulation	-*	-*	-*	-*	-*	-*	-*	Paita, effsp
O30	Anchovy landings of	Landings cumulated over the simulation	+*	+*	+*	+*	-	+	-	Paita,

Spanish fleets	MgtStr, effsp

[a] Direction of the effect of each management strategy on the metric compared to the base case (+ positive effect ; - negative effect). '*' indicates significance of the effect (pvalue <0.05).

[b] Main factors to which the metric is sensitive: MgtStr: management strategies; spPrice: flexibility coefficients of price equations for the species; effp1: effort level of pair trawlers profile 1; Gro: coefficients of anchovy growth curve; priceGas: scenarios of fuel price; effb2: effort level of purse seiners from Brittany; païta: level of live bait catches of anchovy by Spanish fleets for tuna fishing; effsp: effort level of Spanish fleets.[c] Greenstreet et al. (2009)

Table 6: Indicators related to revenues of the fishing industry and direction and significance of the effect of management scenarios on their value.

Management effect on revenue

	Metrics	Description and reference computation method	Management effect[a] 1.TAC	2.TAC-MPA1	3.TAC-MPA2	4.TAC-MPA3	5.MPA1	6.MPA2	7.MPA3	Sensitivity[b]
O31	Long term revenue p1	Gross revenue cumulated over the simulation period	-*	-*	-*	-*	-*	-*	-*	spPrice, effp1
O32	Long term revenue p2		-	-*	-*	-*	-*	-*	-*	effp2, spPrice
O33	Long term revenue b1		-	-*	-*	-*	-*	-*	-*	effb1
O34	Long term revenue b2		-	-*	-*	-*	-*	-*	-*	effb2, spPrice
O35	Short term revenue p1	Minimum annual gross revenue	+	-*	-*	-*	-*	-*	-*	effp1, spPrice
O36	Short term revenue p2		+	-*	-*	-*	-*	-*	-*	effp2, spPrice
O37	Short term revenue b1		+	-*	-*	-*	-*	-*	-*	effb1
O38	Short term revenue b2		+	-*	-*	-*	-*	-*	-*	effb2, spPrice
O39	Trend in revenue p1	Linear trend in gross revenue	+*	+*	+*	+*	+	+	+	Paita, hypH

O40	Trend in revenue p2			+*	+*	+*	+*	+	+	+	Paita, spPrice, hypH
O41	Trend in revenue b1			+	+	+	+	+	+	+	spPrice, paita, effsp
O42	Trend in revenue b2			+	+*	+*	+*	+	+	+	Rsar, effb2, spPrice
O43	Variability in annual gross revenue p1	Standard deviation of annual values	Kraak et al., 2008	-*	-*	-*	-*	-*	-*	-*	spPrice
O44	Variability in annual gross revenue p2			-*	-*	-	-*	-*	-	-*	spPrice
O45	Variability in annual gross revenue b1			-*	-*	-*	-*	-	-*	-	effb1, MgtStr
O46	Variability in annual gross revenue b2			-*	-*	-*	-*	-*	-*	-*	spPrice

[a] Direction of the effect of each management strategy on the metric compared to the base case (+ positive effect ; - negative effect). '*' indicates significance of the effect (pvalue <0.05).

[b] Main factors to which the metric is sensitive p1: pair trawlers profile 1; p2: pair trawlers profile 2; b1:purse seiners from the Basque Country; b2:purse seiners from Brittany ; spPrice: flexibility coefficients of species price equations ; effp1: effort level of pair trawlers profil 1; effp2: effort level of pair trawlers profil 2; païta: level of live bait catches of anchovy by Spanish fleets for tuna fishing; hypH: hypotheses on inter-annual variability of survival of larvae and migration; effsp: effort level of Spanish fleets; Rsar: sardine recruitment; effb2: effort level of purse seiners from Brittany; MgtStr: management strategies.

Table 7: Indicators related to the price of anchovy and direction and significance of the effect of management scenarios on their value.

Management effect on anchovy price										
	Metrics	Expected effect[a]	Management effect[b]							Sensitivity[c]
			1.TAC	2.TAC-MPA1	3.TAC-MPA2	4.TAC-MPA3	5.MPA1	6.MPA2	7.MPA3	
O47	Average annual price anchovy category 10 (large)	Prices are expected to rise when MPA are enforced	+*	+*	+*	+*	+*	+*	+*	spPrice
O48	Average annual price anchovy category 40 (small)		+*	+*	+*	+*	+*	+*	+*	paita
O49	Variability of average annual price anchovy cat 10		+*	+*	+*	+*	a	+	+	spPrice
O50	Variability of average annual price anchovy cat 40		+	-*	-	-*	-	+	-	hypH

[a] When described in the literature, expected direction of change in the value of the metric due to management strategies.

[b] Direction of the effect of each management strategy on the metric compared to the base case (+ positive effect ; - negative effect). '*' indicates significance of the effect (pvalue <0.05).

[c] Main factors to which the metric is sensitive: spPrice: flexibility coefficients of species price equations ; païta: level of live bait catches of anchovy by Spanish fleets for tuna fishing; hypH: hypotheses on inter-annual variability of survival of larvae and migration.

Table 8: Indicators related to fuel expenses for the French fleets and direction and significance of the effect of management scenarios on their value.

Management effect on Fuel costs

	Indicator	reference	Description and computation method	Management effect[a] 1.TAC	2.TAC-MPA1	3.TAC-MPA2	4.TAC-MPA3	5.MPA1	6.MPA2	7.MPA3	Sensitivity[b]
O51	Fuel cost fh^{-1} p1			-*	-	-*	-	+*	+	+*	PriceGas
O52	Fuel cost fh^{-1} p2			-*	+	-		+	+	+	PriceGas
O53	Fuel cost fh^{-1} b1			+*	+*	+*	-	-	+*	-	effb1
O54	Fuel cost fh^{-1} b2			+	+	+	+	+	+	+	PriceGas
O55	Trends in fuel costs p1	Bastardie et al., 2010	Linear trend in fuel costs	+	+	+	+				PriceGas
O56	Trends in fuel costs p2			+	+	+	+				PriceGas
O57	Trends in fuel costs b1			+*	+*	+*	+	+	+	+	PriceGas
O58	Trends in fuel costs b2			-	-	-	-	-	-	-	PriceGas
O59	Fuel dependency p1	Le Corre et al., 2010	Fuel costs / revenu	+	-	-	-				spPrice
O60	Fuel dependency p2			-	-	-	-	-	-	-	spPrice
O61	Fuel dependency b1			+*	+*	+*	+	-	+*	-*	effb1
O62	Fuel dependency b2			+	-	-	-	-	-	-	spPrice
O63	Trend in fuel dependency p1		Linear trend in fuel dependency	-	-	-	-	+	+	+	PriceGas, spPrice
O64	Trend in fuel dependency p2			-	-	-	-	-	-	-	PriceGas
O65	Trend in fuel dependency b1			+	+	+	+	+	+	+*	PriceGas
O66	Trend in fuel dependency b2			+	+	+	+				PriceGas

[a] Direction of the effect of each management strategy on the metric compared to the base case (+ positive effect ; - negative effect). '*' indicates significance of the effect (pvalue <0.05).

[b] Main factors to which the metric is sensitive: p1: pair trawlers profile 1; p2: pair trawlers profile 2; b1:purse seiners from the Basque Country; b2:purse seiners from Brittany ; PriceGas: scenarios of fuel price evolution; spPrice: flexibility coefficients of species price equations ; effb1: effort level of purse seiners from the Basque Country.

Table 9: Parameters to which performance metrics are the most sensitive according to the results of the sensitivity analysis (>10% of explained variability).

	Major source of variability
P1	Hyp. H1/H2, management, païta
P2	Païta, management, effort of Spanish fleet
P3	Païta, management, effort of pair trawler fleet profil 1
P4	Hyp. H1/H2, païta
P5	Management, effort of pair trawler fleet profil 1, Hyp. H1/H2
P6	Hyp. H1/H2

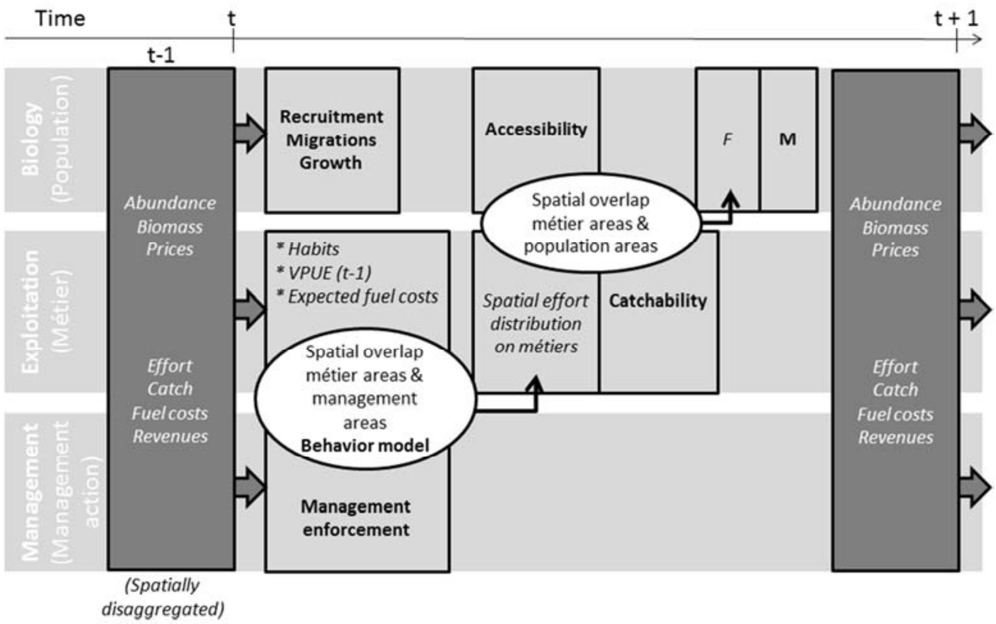

Figure 1: Graphical summary of the ISIS-Fish model of the pelagic fishery in the Bay of Biscay. The chart represents the events simulated by each sub-model (biology, exploitation and management) at each time step (t, month) and the connections between them which result in the computation of the fishing mortality (F). Bolded words represent processes; italic is used to indicate state variables dynamically computed. F: Fishing mortality; M: natural mortality; VPUE: Value landed per Unit of Effort.
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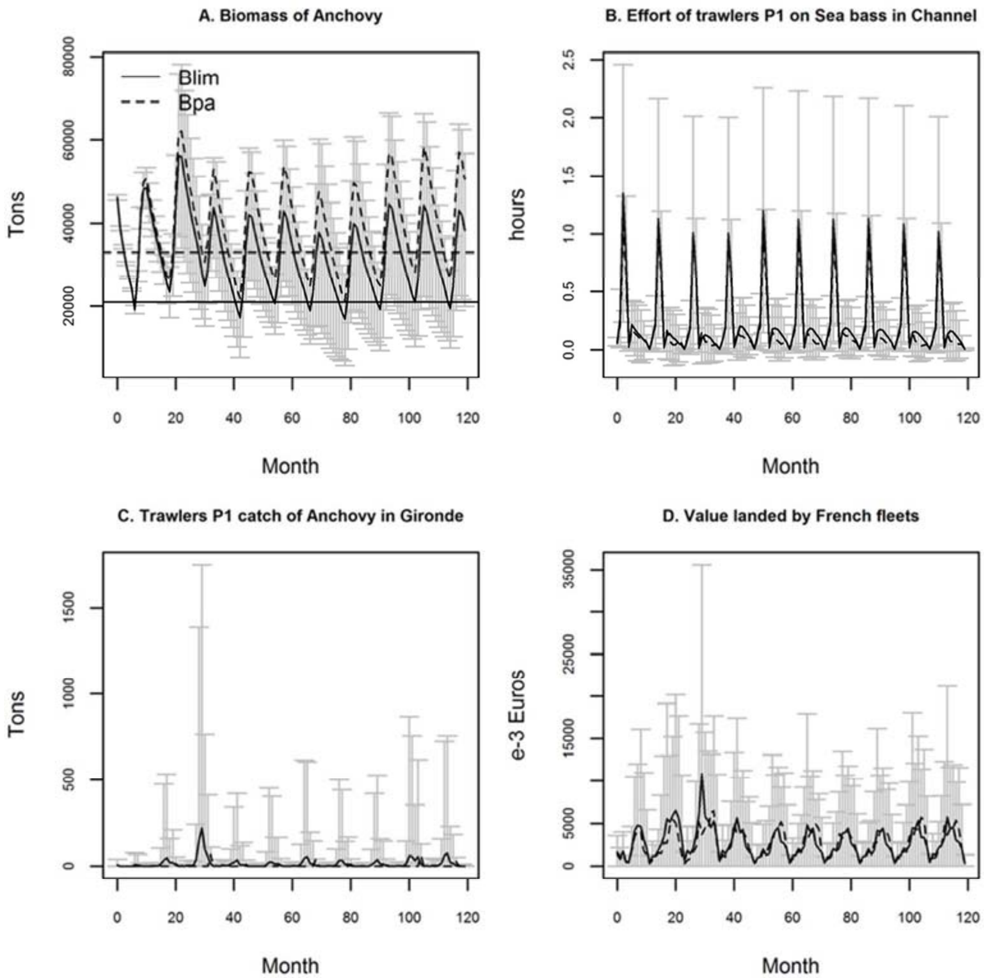

Figure 2: Examples of time series of outputs produced by the ISIS-Fish model of the pelagic fishery in the Bay of Biscay. The average time series obtained in the base case simulation is plotted (continuous bold line) together with 95% confidence intervals derived from the simulation design. The dash line represents the average time series obtained in simulations with management strategy 2 (TAC +MPA 1). A. Monthly biomass of anchovy, with reference levels Blim (biomass limit) and Bpa (precautionary biomass). B. Monthly effort of trawlers profil 1 on métiers targeting sea bass in the Channel. C. Monthly catches of anchovy by trawlers profil 1 in area Gironde. D. Monthly revenues generated by French fleets.
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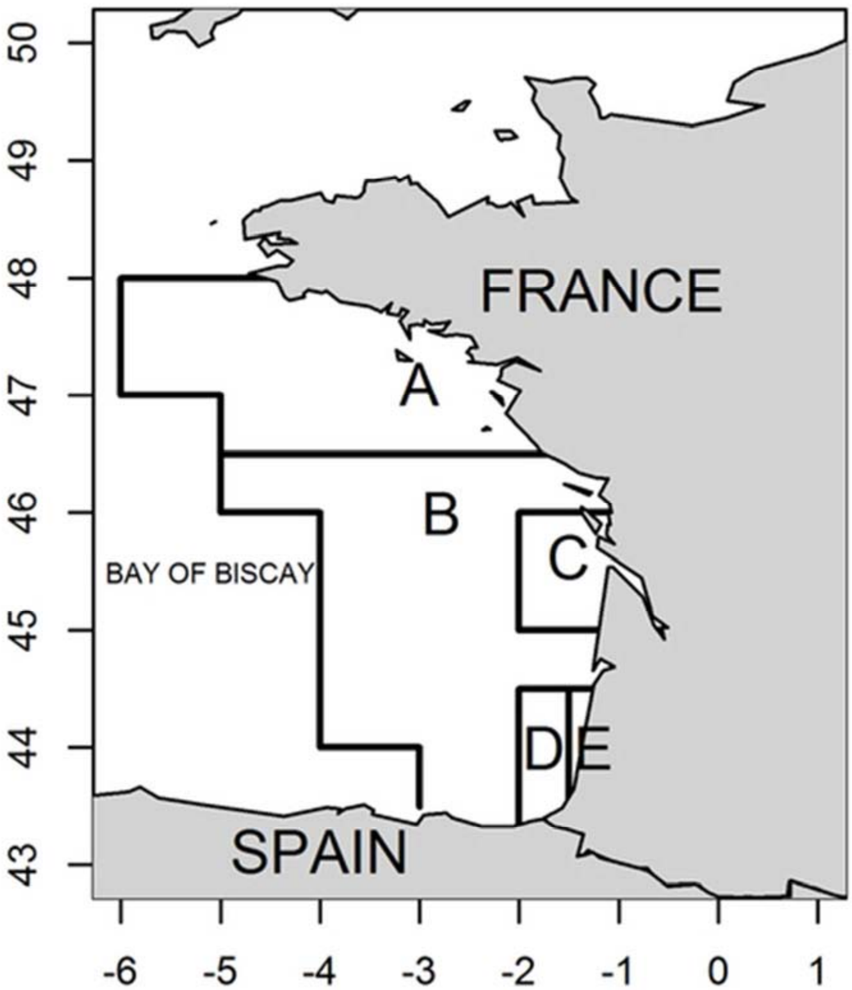

Figure 3: Map of biological and management areas for anchovy in the Bay of Biscay. A North, B. Rochebonne, C. Gironde, D. Landes off, E. Landes coastal.
79x91mm (150 x 150 DPI)

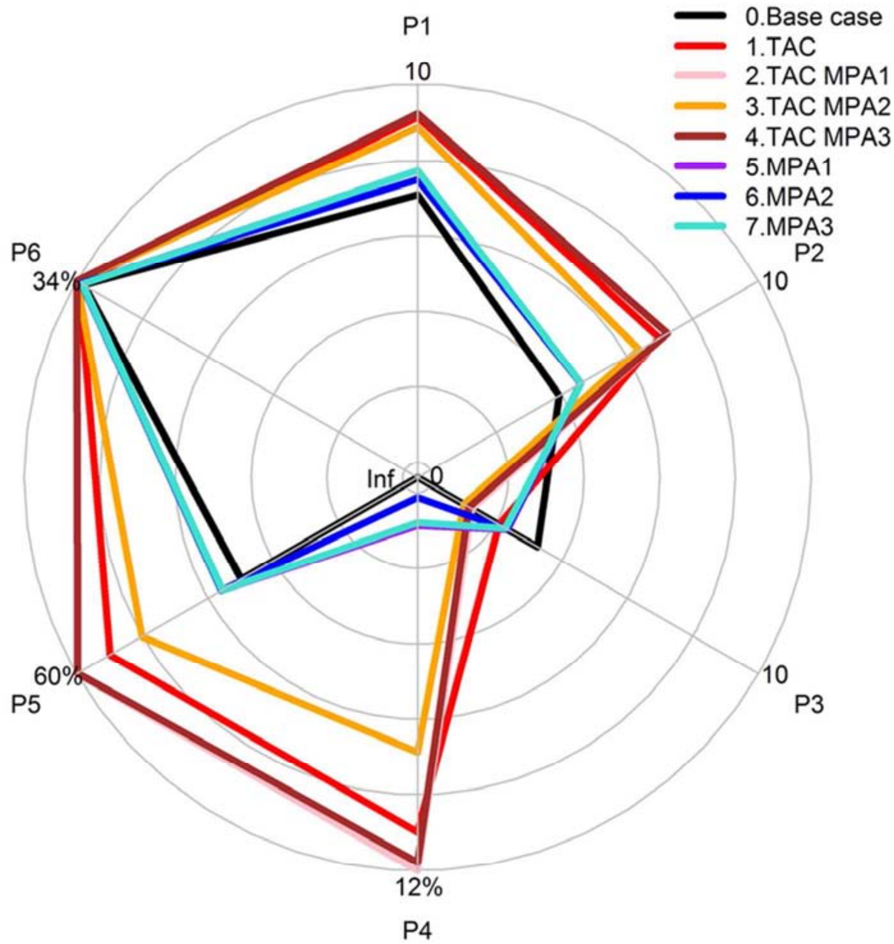

Figure 4: Radar plot of average value obtained in simulation for the performance metrics in each management scenarios. Performance metrics are ordered on the graph according to the dimension to which they referred: biological objectives on the right and economic objectives on the left. Metrics are scaled so that the more on the edge the better. The scale goes from 0 to 10 (simulation duration) for P1 to P3, from 0 to the maximum value observed in simulation for P3. We plot the inverse of P5 and P6 so that the values range from Infinity to the lowest value observed in simulation. P1: no. years with biomass higher than Blim ∈[0;10]; P2: no. years of open closure ∈ [0;10]; P3: no. years with anchovy catch >7000t ∈ [0,max=3.47]; P4: trend in biomass time series ∈ [min;max]; P5: 1/inter-annual variation in anchovy landings ∈ [Infinity;max]; P6: 1/variability of age structure ∈ [Infinity;min]. "min" and "max" stands respectively for minimum and maximum obtained in simulations.
139x139mm (150 x 150 DPI)

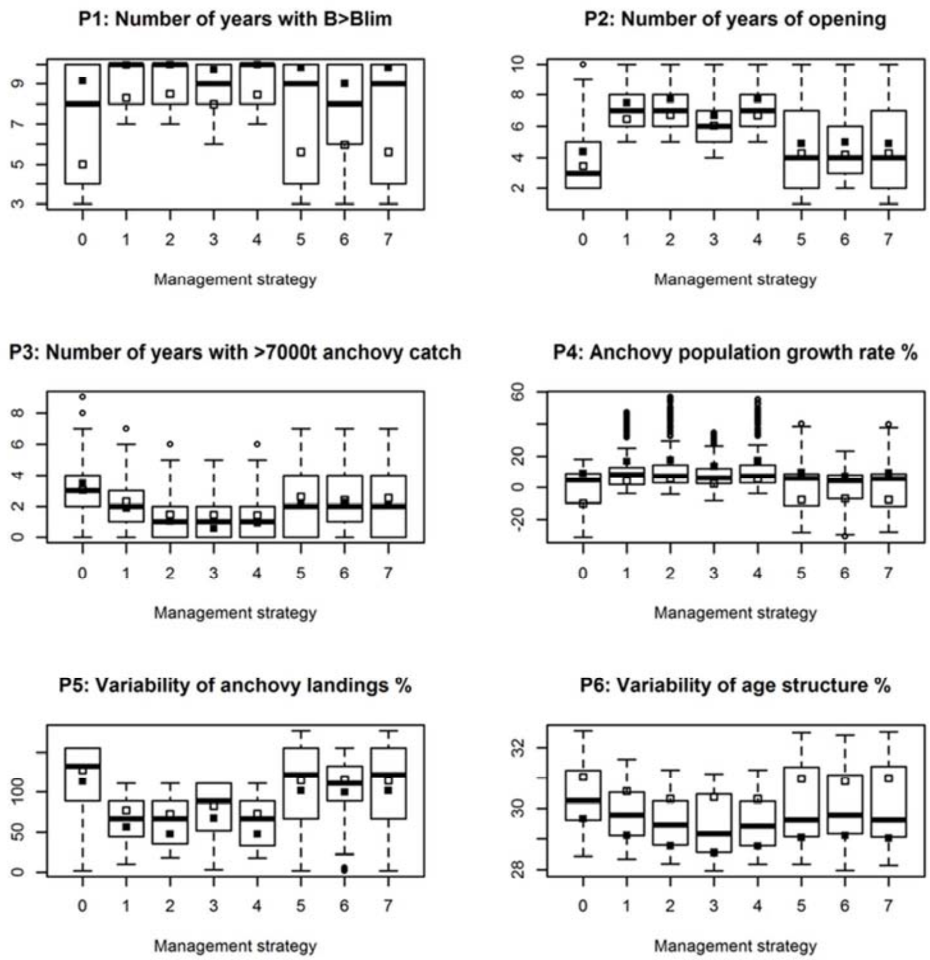

Figure 5: Boxplots of the values of the six performance metrics depending on management strategies (x axis) (boxes represent the median and first and third quartile). The solid square represents the average value obtained in simulations with constant natural mortality and migration scheme, while the open square is the average value in simulations including inter-annual variability in these processes.
Figure 6: Sensitivity indices (16 highest) corresponding to each uncertainty source and management scenario for metric P4: Anchovy population growth rate and P5: Variability of anchovy landings. Sensitivity indices relating to management are in black. ":" represents interaction between two factors. Please report to Table 1 for the meaning of the abbreviations.

139x139mm (150 x 150 DPI)

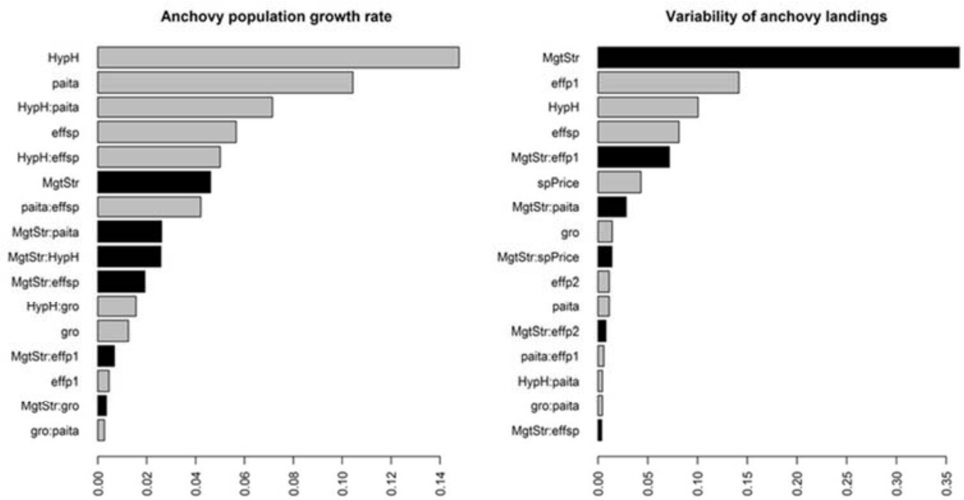

Figure 6: Sensitivity indices (16 highest) corresponding to each uncertainty source and management scenario for metric P4: Anchovy population growth rate and P5: Variability of anchovy landings. Sensitivity indices relating to management are in black. ":" represents interaction between two factors. Please report to Table 1 for the meaning of the abbreviations.
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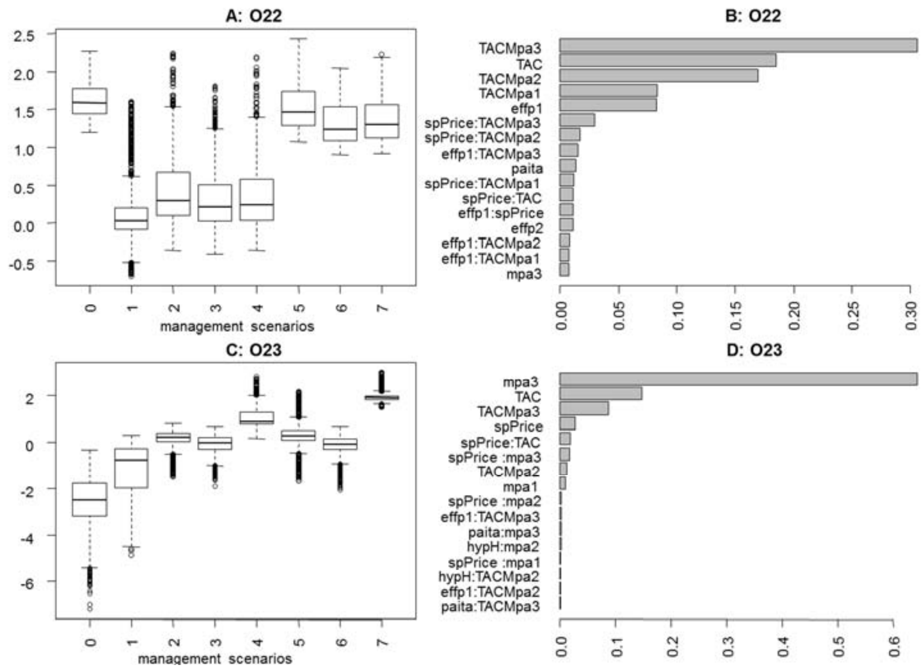

Figure 7: Effect of management scenarios on the allocation of effort of trawlers profile 1 on métiers, metrics O22 (top) and O23 (bottom). A and C: Simulated values of the metric depending on management scenario (x axis) (boxes represent the median and first and third quartile). B and D:. Sensitivity indices (16 highest) of the metric corresponding to each uncertainty source and management scenario and computed based on variance decomposition; ":" represents interaction between two factors. Please report to Table 1 for the meaning of the abbreviations.
381x254mm (96 x 96 DPI)