ISIS-FLR : An FLR-based bioeconomic operating model for mixed fisheries : framework and application

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Abstract

A main issue in the dynamics of mixed fisheries is that of technical interactions, leading to incidental catch and discarding. Technical interactions largely depend on the allocation of fishing effort between metiers and fishing grounds which in turn is tightly linked to economic conditions and to the expected profitability of alternative options for fishing effort allocation. We developed a bioeconomic fishery model to investigate these issues, and in particular to explore the possibilities of mitigating these interactions through appropriate policy options. The bioeconomic model was developed using and creating FLR (`http://www.flr-project.org`) packages as part of the EFIMAS project (`http://europa.eu.int/comm/research/fp6/ssp/efimas_en.htm`). The model is spatially- and seasonally-explicit, it considers population dynamics, exploitation dynamics and policies are explicitly modelled, building in the fishery model underlying the ISIS-Fish software (`http://www.ifremer.fr/`

Preprint submitted to Elsevier *13 September 2007*

isis-fish\). The model is applied to the hake-nephrops fishery in the Bay of Biscay. The fishery generates a large amount of by-catch of juvenile hake, particularly at recruitment time. We modelled the dynamics of the main fleets exploiting hake and nephrops, and investigated the consequences of several policy options, including present ones (Total Allowable Catch) and gear technical measures, and alternative options including Marine Protected Areas, closed seasons, and selective devices.

Key words: Fisheries management model, Fisheries Library in R (F.L.R.), mixed fisheries, M.P.A., *Merluccius merluccius*, *Nephrops norvegicus*

1 Introduction

Mixed fisheries are characterized by a set of fleets in competition for the resource harvesting not a single but a combination of species along a mosaic of fishing grounds (Laurec *et al.* (1991); Marchal *et al.* (2002)). Before each fishing trip, fishermen used to chose a species or a set of species to be caught regarding their expected profitability or the remaining TAC, etc. (Christensen and Raakjaer, 2006). But in mixed fisheries, the ability of the fishers to target individual species is generally assumed to be limited using a selection of gear, fishing ground and target species and may depends on the spatially and seasonally pattern of the availability of this species in regard to its covariance with other species. This implies that species cannot always be harvested separately because of technical interactions among fishing activities (TECTAC, 2006). Such a complexity of interactions in this multi-fleets and multi-stocks context could partly explain the difficulty to implement efficient regulations

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for a sustainable exploitation of fisheries. For example, the TAC management is no longer efficient while there are fishing activities incidentally catching populations for which the TAC is already reached (Biais, 1995). Equally, illegal catches or disproportionate discards will not be avoided if a fleet is unable to change its fishing activity for economic reason (Hansen *et al.*, 2006). Conversely, if a given fleet adapts its fishing activity in agreement to the remaining TAC or to the variation of the stock abundance, the neglectful of fisher's behaviour could lead to underestimate the incidence on other stocks of a change in spatial effort allocation and/or gear and/or targeted species while TAC regulations are implemented. The mixed species aspect of fisheries would be rather addressed using fleet-based regulations with economic and fishermen's behaviour consideration instead of single stock-based regulations (Ratz *et al.*, 2007). A common solution for better fishing practice and stock preservation would be to reduce as far as possible the technical interactions between fishing activities. In this goal, alternative management measures have been suggested (TECTAC, 2006) such as:

(1) an alteration of the selective performance of fishing gears as a direct way to control the fishing mortality on the stock, both in fisheries targeting a given stock as well as in those which are not directed to the species but have a significant level of discards for this stock.

(2) The creation of Marine Protected Areas (MPA) as a management rule to protect particular stages in the stock life-history (spawning, etc.) from fishing. Because of the efficiency of the MPA may depend on the size, the seasonality and the location of the closure, these MPA features have to be investigated.

Fisheries description and modelling should be performed with considerations of the economic sustainability of evolved fleets. It obvious that the best way to achieve the stock conservation objective should be to totally close the fisheries, but it is a non-sense in economic and social terms. Management of fisheries include economic and social objectives that require to test short-term and long-term consequences of implementing conservation measures for impacted fishing activities (Walters and Martell (2004); Kjaersgaard and Andersen (2007)). In a multi-fleet context with inherent technical interactions, revenues of different fishing activities are more or less inter-dependent and the effects of regulations applied to a set of fishing activities have shown to be considered simultaneously as the result of the positive or negative effects from each fishing activity to each others (Ulrich *et al.*, 2002). For example, a bio-economic model should aims at quantifying how much the catches from fleets not targeting the stock (i.e. producing by-catches) affect the performance of fleets targeting this particular stock. In a regulation context, it also needs to test if the activity change from a fishing activity to another is economically viable (i.e. evaluate the potential of substitutability between the main and alternative species).

Because of real-time experiments in fisheries are impossible to carry out and retrospective analysis of implemented policy option is still scarce, models of fisheries are needed to test management scenarios. Pelletier and Mahevas (2005) give a recent review of models enable to mimic the stock dynamics in interaction with the variation of the fishing pressure from fleets dynamics and simple management rules implementation. Few among these models aims at describing fisheries in multi-fleet way using economic inputs and outputs and evaluate the reciprocal dependency of revenue between fleets (BECHAMEL in Ulrich *et al.* (2002); BEMMFISH in Guillen *et al.* (2004), TEMAS in Ulrich *et al.* (2007), MEPHISTO in Lleonart *et al.* (2003)). Furthermore, in order to draw as far as possible an accurate picture of fisheries and address the mixed fisheries issue, some additional features of the fisheries have been taking into account with models performing stock and exploitation dynamics in a spatially and seasonally explicit way (see the review of Pelletier and Mahevas (2005)). Exploited stocks are generally not uniformly distributed in space and time but display spatio-temporal patterns. Many species are known to migrate between different habitats during their life span with seasonal aggregation of spawners and juveniles. Equally, spatial allocation of the fishing effort is not uniformly distributed but depends on fisher behaviours which looks for fish concentration and having a bounded range of action from the harbour departure. Since effort and stock patterns are suspected to be highly correlated, some biases could weaken the link between the fishing mortality and the effort if spatio-temporal dimension is neglected. Space and time dimensions in models enable to investigate and design alternative management such as MPAs (size, season, location) regarding the dynamic allocation of fishing effort. In this way, ISIS-Fish model ('Integration of Spatial Information for FISHeries simulation ', Mahevas and Pelletier (2004)) is designed as a generic simulation tool to quantify the impact of management rules on multi-species, multi-fleet fisheries. The underlying fishery model takes into account of the spatial and seasonal dynamics of each population and each fishing activity as well as fishermen's behaviour in response to one or a combination of management rules which are explicitly modelled. In addition, the most recent version of ISIS-Fish add an economic module enables to compute fleet and fishing activity based costs and fleet revenues. Other recent trial are dealing with fisheries modelling suggesting disaggregated space and time dimension. ISIS-fish model is a simulation tool which could be useful to project forward the state of fisheries in the future regarding to initial input conditions.

FLR (i.e. 'Fisheries libraries' in R; Kell *et al.* (2007)) aims at developing a software suite to test alternative management strategies conducted within a common generic framework for fisheries modelling. FLR is developed using R (R Development Core Team, 2007), an environment and computer language for statistical computing and graphics which is highly extensible. The FLR framework is implemented using object-oriented programming (OOP) by making use of the S4 classes within R (Chambers, 2000). FLR constitute an extension of R which suggests different elements of fisheries systems (stocks, fleets, assessment methods, etc.) represented as predefined classes of objects. Like R, FLR is an OpenSource project (under the GNU General Public License, version 2) means that the source code is available to the users (FLR classes could be downloaded on the main web page for the project - `http://flr-project.org`) and could be reused and modified. Beyond FLR, existing models for management of fisheries such as ISIS-Fish already incorporates mixed fisheries, multispecies and economic models and it appears relevant to plug existing models to the management procedure supported by the FLR platform (eXtended Survival Analysis, shorterm forecast, etc.). Hence, the FLR project suggests to reuse the set of developed tools and packages to implement blocks of a the full feedback management procedure (operating model, observation error model, stock assessment model, decision making model, implementation error model and feedback; examples in Kell *et al.* (2007); Pastoors *et al.* (2007)) from the ISIS-Fish operating model. Then, in this paper we developed a FLR-based model called 'ISIS-FLR' entirely coded in R using the FLR framework as a toolbox to generate fishery-related objects from existing FLR classes. However, since the model encompasses the complex structure of mixed fisheries and emphasizes spatial and seasonal aspects, new classes of objects have been defined for handling objects with specific extended properties. In this paper we aim at:

(i) proposing FLR objects that are consistent with the FLR framework and enable to consider mixed fisheries issues

(ii) show how ISIS-Fish can be recoded based on this proposed object structure into the tool ISIS-FLR

The relevance of ISIS-FLR as an operating model for testing management procedures for mixed fisheries will be illustrated from the example of the Hake and Nephrops fisheries of the Bay of Biscay. We will in particular show how fleet dynamics, short-term fishers behaviour and technical interactions can be modelled and how technical measures on gear selectivity and MPA management scenarios can be tested with this tool.

2 Methods

2.1 From ISIS-Fish to ISIS-FLR

ISIS-FLR model defines a set of FLR-like classes and methods encapsulated in a R package named 'FLIsis' which is available for download on the FLR web site. The conceptual representation of a fishery in the 'ISIS-FLR' model were being built from the 'ISIS-Fish 'model (Mahevas and Pelletier, 2004). The model is a spatially and seasonally explicit multi-fleet, multi-stock model taking into account of the response of fishermen to a range of management rules through dynamic allocation of fishing effort. Fishery simulations result from the interaction between four sub-models : (i) a population sub-model which simulate the demographic processes for each species over space and time; linked with (ii) an exploitation sub-model by the relationship between fishing effort of the fleets and fishing mortality; the fishing mortality depending on (iii) the management sub-model altering the spatio-temporal distribution of the fishing effort based on management constraints and on the response of fishers to these constraints; finally (iv) a bioeconomic model computes revenue from landings and fish price. Beyond traditional management rules (e.g. T.A.C.) it is assumed that alternative management options could be suggested by monitoring the spatio-temporal covariance between population and exploitation dynamics. Then, at each discretized time step, fisheries dynamics is determined by the spatial overlap between population areas, fishing activity areas and management areas. The model is a monthly time step model and uses a regular grid of cells to discretize the fishery region (the ices square resolution of space by default) and the degree of discretization for both of these features could be set up as needed by the user.

The translation of spatially- and seasonnally- explicit ISIS-Fish objects toward FLR environment have been facilited using basic FLR existing classes (Full details of FLR classes and their internal structure are provided on the FLR web site) and in particular the FLR lower-level class named ‘FLQuant’. This class provide the basic structure to design time and area-desagregated arrays of data. ‘FLQuant’ objects are 5-dimensions array of data: the first dimension can be set by the users (e.g. ‘Age’, ‘Length’, ‘Vessel type’) and the other dimensions are ‘Year’, ‘Unit’ (e.g. ‘Sex’, ‘Spawning type’), ‘Season’ and ‘Area’. These dimensions are common with the existing ISIS-Fish’ s basic object dimensions. Different FLQuants have been grouped into FLR classes and constitute attributes of these classes (generally called ‘slots’ in the R OOP vocabular; Chambers (2000)). Figure 1 depicts the representation of the fishery of the present model as a set of composite FLR-shaped classes nested by common slots acting as relational keys between objects. For the sake of simplicity, related-fishery region data used as input in ISIS-FLR are currently stored as text files and consequently do not require additional software (e.g. database) than R statistical language. Data are loaded in the R working space and constitute a list of slots in the main class of the ISIS-FLR application we called 'FLIsis' . Then, the core of the ISIS-FLR model is the FLIsis class we built and which acts as a class manager by holding the set of input data and the combination of management rules (and related parameters) to be tested by sequential simulations. All ISIS-FLR objects are initially created at the beginning of the simulation and act as collectors of the data processed by the simulation loop and equation computation over time steps (Table 1).

2.2 population dynamic

Steps for simulation of age-disaggregated and spatially- and seasonnally-explicit dynamic of populations are described in Appendix 1. Disaggregated demographic processes simulations are facilited by the use of the area and season-desaggregated FLQuant objects. For our purpose, the existing FLR class named FLBiol have also be reused suggesting a set of FLQuant objects holding all the age-, time- and area-desaggregated relevant information to compute demographic processes (weight-at-age, fecundity-at-age, natural mortality, etc.) over discrete time steps. We have largely extended this class to create a 'FLBiol2' class (Table 1) which holds additional information (i.e. slots) which are (i) information about recruitment-specific areas, reproduction areas or other type of areas such as nurseries constitute slots of the FLBiol2 class ;

(ii) migration coefficients from zones to another with an attached method to perform migration at relevant timing; (iii) ogives of reproduction and recruitment providing timing for these processes; (iv) additional slots to compute a stock-eggs relationship for reproduction such as sex ratio, eggs mortality, etc. (v) a matrix of ‘age ’ change (or ‘length ’or ‘stage ’ change). Hence, a FLBiol2 object with its specific slots can be initialized at the beginning of the simulation for each simulated stock.

2.3 exploitation dynamic

Several fleets are supported as set of vessels with distinct physical characteristics (e.g. length, engine power, etc.) mainly because they result in distinct travelling times, fishing powers and corresponding costs. Further, to take into account of spatio-temporal heterogeneity of fishing activities, ‘metiers’ (also called ‘trip type’, ‘rigging’ or only ‘gear’) are defined to constitute each a particular spatio-temporal fishing activity of the fleet. A metier is defined as a unique arrangement of a gear, one or a set of target species and a fishing ground (Mahevas and Pelletier, 2004). Within each strategy, the distribution of fishing effort between metiers over the year is dictated either by a static activity calendar per metier (a particular type of calendar constitute a strategy) or by a dynamic allocation of effort model into metiers (e.g. given by the outputs of a Random Utility Model) and mimics the splitting up of the global effort of the strategy into effort per metier (Appendix 2). The development of new designed FLR-shaped classes (Table 1) were required to store specific features of the ISIS-Fish way of modelling. Then, the FLSetOfVessels class, as an extended version of the original FLR FLFleet class, enables to define a set of vessels sharing physical characteristics but also sharing the same strategy i.e. the same sequence of fishing activities or metiers over time. Consequently, each fleet could be modelled by one or several FLSetOfVessels objects, as many as possible strategies. Each FLSetOfVessels object has got a list of FLMetier objects to describe the metiers practiced within a given strategy. The key allocation of the total activity into activity in each metier of the FLSetOfVessels object is hold in a particular slot named 'activity'having metier names as first dimension. Then, various fishing activities occuring on different areas and possibly varying over time could be set up for each FLsetOfVessels. Metier zones constitute a list of cells among fishery region cells.

In this mixed fishery model, a same stock is harvested by different metiers. Then, over the simulation loop, at each time step, on each cell of the grid, the total age and cell-disaggregated fishing mortality on stocks $F_{stock,age,cell}$ is computed as the sum of the fishing mortality per fleet per metier (details in Appendix 3) and applied on the stock. Conversely to ISIS-Fish, two ways have been set up to applied zone-desaggregated fishing mortalities on stocks depending on the user-chosen spatial scale:

(1) The fishing mortality $F_{metier,stock}$ is applied cell by cell creating local depletion in stock abundance.

(2) The fishing mortality $F_{metier,stock}$ is applied metier zone by metier zone by summing F over cells belonging to a same metier zone and in this case:

$$F(t)_{fleet,metier,stock,age,cell} = F(t)_{fleet,metier,stock,age,cell} \times nbIntersectCells_{metier} \tag{2.1}$$

with $nbIntersectCells$ the metier-related number of cells of the intersection between the metier zone and the biological zone for the concerned stock.

With the assumption that the fishing mortality is instantaneously applied at the beginning of each time step, total catches for each stock are computed from total fishing mortality and dispatched into catches per metier C depending on the contribution per metier to the total mortality applied to the stock following:

$$C(t)_{fleet,metier,stock,age} = \sum_{1}^{i}[\frac{F(t)_{stock,age,cell_i}}{F(t)_{stock,age,cell_i} + M(t)_{stock,age,cell_i}} \times N(1 - e^{F_{stock,age,cell_i}+M_{stock,age,cell_i}}) \times \frac{F(t)_{fleet,metier,stock,age,cell_i}}{F(t)_{stock,age,cell_i}}] \tag{2.2}$$

with M the natural mortality. A proportion of catches is discarded based on the age-disaggregated ogive of discards for this metier, and the remaining part of catches yields the landings.

2.4 economic model

The economic sub-model explicits fleet and metier cost definition and dynamic of fleet revenues from landings (Appendix 4). The aim is to (i) assess the short-term economic effects and viability of management measures, and (ii) take into account the short-term response of fishers (i.e. in terms of spatio-temporal reallocation of effort) to economic indicators or market events. Then, owner margin and vessel margin are computed from economic characteristics of metiers as the most recent version of ISIS-Fish is also suggesting (version 3.0). Additional new FLR-shaped classes (Table 1) were required to take into account of economic terms which are: (i) the FLMarket class which enables to compute metier-stock specific prices. A list of FLMarket objects in the simulation stores stock-specific parameters attached to a market place to compute age-structured fish price from a price equation (e.g. supply and offer law) using the total landings on the concerned market; (ii) the FLCostFleet and FLCostMetier classes which store cost structure of fishing activities impacting dynamics at either fleet level (insurance costs, etc.) or at metier level (fuel costs may depends on the used gear and the visited area, etc.). It is assumed that all vessels of a given fleet share similar cost structure which seems realistic since fleets are set of vessels with similar physical characteristics. Cost structure is fixed over the simulation process while the total cost depends on the effort allocated on each fishing activity at each time step; (iii) the FLRevFleet and FLRevMetier classes which compute revenues of fishing activities. The gross return for a particular metier are computed from fish price and age-structured landings of the metier. The gross return from other species (i.e. species whose population dynamics is not explicitaly simulated) is added as a linear function of the metier effort. Net revenues are then computed from gross return minus costs for fishing. Then, economic objects are linked with FLSetOfVessels and FLMetier objects using common slots as relational keys. Further, capital dynamics is also supported through these classes and may be used to implement an entry/exit model of vessels to/from the fishery. Equally, a model option enables economic outputs to influence the dynamic of effort allocation between metiers for the next time step.

2.5 management rules

As enabled by the flexibility of FLR, the settings for management sub-model are stored into a new FLR-shaped class (we named 'FLMgtRules'). Management rules runs over time steps either at predefined steps from the database or dynamically in response to simulation events (e.g. TAC reached, etc.). Hence, a combination of management rules and all their related values can be tested by sending this combination as argument during the creation of the FLIsis manager class. Using a grid of simulations, these management rules are evaluated before each new simulation using new values as arguments of each rules. Conversely, management rules could occur over the simulation depending on internal events. A particular management rule implemented in ISIS-FLR is MPA rule. With this rule, Marine Protected Areas could be set up as a partial or total closure of all or chosen fishing activities on predefined or dynamic zones at predefined or dynamic times. Assumptions are needed concerning fishers behaviours facing to the management rule constraint. In case of MPAs, two possibility are assumed for the reallocation of the fishing effort: (i) activities of possible metier for each fleet are reallocated to the remaining cells of metier zones; (ii) for a given fleet activities from metiers using forbidden gears is reallocated on metiers using allowed gears. If all metier cells are closed for a given metier, the activity of the concerned metier is reallocated to other possible metiers of the fleet. Finally, if all metier cells are closed for all possible metiers, the activity of the concerned fleet is set up to 0. The alteration of the selectivity of the used gears could also be set up. If this rule occurs, selectivity curves from gear-specific selectivity equations are re-calculated using desired values for the technical parameter (e.g. mesh size).

2.6 Conditioning on Northern Hake/Nephrops mixed fishery

The Hake/Nephrops mixed fishery is located on the continental shelf of the Bay of Biscay (ICES VIIIab) and involved both french and spanish fleets.

Fleet definition for this fishery was performed by Mahevas et al. (2006) in the TECTAC project framework. The modelled french fishing activity is a set of 8 FLSetOfVessels i.e. a total of 206 vessels distributed into 2 vessel types (intermediate: 12-24 meters; large: > 24 meters) attached to 1 harbour and displaying 4 strategies of activity pattern over the year. The spanish fleet is described by 6 FLSetOfVessels i.e. a total of 69 vessels distributed into 2 vessel types (20-29 meters; 30-39 meters) attached to 2 harbours and displaying 2 strategies. Specific trip types attached to these fleets are described in Table 2. Spatio-temporal distribution of fleet efforts are driven by related-metiers zones and activities over year using a static allocation of effort per metier over time obtained from data analysis (Figure 1; TECTAC (2006)). Metiers use either single or pair bottom trawls or gillnets for which the age-specific selective behaviour have been assessed (Table 6).

Drouineau *et al.* (2006) previously applied the ISIS-Fish model on the mixed fishery of hake/nephrops and the present study partly reuse the same value for parameters linked to the biological model. The spatial distribution of Nephrops is restricted to the 'Grande Vasiere' (ICES VIII) whereas hake is located along all the shelf of the Bay of Biscay (Figure 3) and the Celtic sea (ICES VII). The effect of the reduction to the Bay of Biscay area in the present study is not well known and it is assumed that reproduction and recruitment areas may be distinct between this region and the Celtic Sea like ICES which assume two distincts stocks. Initial population abundances were taken from the 2003 ICES stock assessement and were uniformly distributed over the area of presence of the stock in the Bay of Biscay. Nephrops stock is sedentary while Hake stock show seasonal ontogenic migrations between areas with agregation on reproduction zone along the shelf edge at the beginning of the reproduction season (January) and dispersion over the whole of presence area at the end of the season (July) (Table 4; Quero and Vayne (1997)). The migration in or out of the Bay of Biscay have not been taken into account because of lack of data. For both stocks, age and season-specific catchabilities were estimated based on data analysis of log-books data and catch-at-length information (Drouineau *et al.*, 2006). The spanish fleets data result from analysis of logbook and activity data from the AZTI-tecnalia database. Related-economic parameters for french fleets and metiers and market place parameters were obtained from data collected by the Fisheries Information System of Ifremer via surveys of individual vessel owners (year 2003) (TECTAC, 2006). Spanish economic data are obtained from the Statistical Service of the Departement of Agriculture (Fisheries and Food of the Basque Government).

Deterministic simulations were running to test two management scenarios from the data set which defined the initial conditions assuming total compliance of fishermen for both scenarios:

(1) *MPA scenario.* Northern hake use to spawn from February through July along the shelf edge, the main areas extending from north of the Bay of Biscay to the south and west Ireland (ICES 2006). Large part of the hake catches are obtained during the first quarter of the year when the spawning period occurs. Data have shown that there are specific ICES rectangles where high catches occur reiteratively year after year, and in particular for the spanish fleets using VHVO gears (i.e. 'Very High Vertical Opening' nets). Thus, a possible management scenario is to close these rectangles (contiguous 22E4, 23E5, 23E4 and 22E5; contiguous 20E7 and 19E7) to the VHVO pair trawlers and to the TTBLN and OTBLN french trawlers from February to May.

(2) *selective gear scenario.* In order to reduce the Hake discards from by-catch of juveniles for the fleets targeting nephrops the impact on an increasing minimum mesh size for trawl gears (70 mm, 100 mm, 130 mm which respectively correspond to the 50% retention age in years of 2.5, 4.4 and 6.3 for the Hake and 0.5, 1.2 and 2.1 for Nephrops with our settings for trawl gears) is tested on the fishery in terms of stock evolution, landings and fleet revenues.

The aim of this paper is to illustrate some trends in the fishery response to various management options rather than provide absolute numbers about stock abundance or catches. Results are showed in relative values of each tested scenario in regards to the scenario of reference (70 mm for mesh size of trawl gears and no MPA application). Then, two diagnostic plots are suggested here: (i) The landings ratio $Lratio_t$ at the horizon time (t = 5 years) is given by $Lratio_{t=5} = \frac{\sum_{t=1}^{5} L_t - \sum_{t=1}^{5} Lref_t}{\sum_{t=1}^{5} L_{ref,t}} \times 100$ with $Lref_t$ the landing of the simulation of reference;(ii) the slope and the intercept of the linear regression of landing ratios over time. In this case the slope parameter is the percent of gain (if positive) or loss (if negative) per year while the intercept parameter represent the immediate (i.e. at t=0) loss or gain of landings with respect to the landing of reference. In addition, time of recovery to the reference level can be computed and traced using the relation $t_{recovery} = \frac{Lratio_t - intercept}{slope}$ with $Lratio_t = 0$, occuring when landing of the tested scenario L equal the landing of reference $Lref$. A cluster analysis was performed using the ward criteria in order to depict and make the representation clearer of group of responses of metiers to the tested combination of management rules.

In addition, simulation results are known to be sensitive to population parameters such as catchability coefficients and natural mortality values attached to the stocks for which data analysis showed difficulties to estimate (Drouineau *et al.*, 2006). Nevertheless, FLIsis enables a serie of simulations (i.e. an experiment plan) to be launched to test different values of parameters. Then, in order to check if trends still exist with respect to uncertainty on parameter values, several simulations were ran using a range of values for the capturability and natural mortality of simulated stocks.

3 Results

3.1 effect on stock biomasses

Under the assumption of a constant exploitation pattern from a year to the next, the deterministic simulated biomass trajectories of stocks (Figure 4; scenario of reference i.e. 70mm of mesh size/ no MPA) showed variations depending on the occurence of age-structured biological events (recruitment, class change at the beginning of the year) and depending on the interactions between spatio-temporal allocation of fishing effort and the spatio-temporal occurence of the stock (migration pattern). Both stock evolution was impacted by the tested management scenarios since all tested scenarios led to higher biomass levels (same result in abundance) at the 5-years horizon time with respect to the scenario of reference. For both stocks the higher level of biomass was reached with the scenario combining a 130 mm of mesh size for trawlers with the MPA application altering the spatio-temporal allocation of fishing effort (+35.2% and +16.7% for Nephrops and Hake respectively under 130mm/MPA scenario). MPA occured during the Hake spawning period and protect a part of the stock from fishing. All Hake ages were protected in cells

23E4, 22E4 and 22E5 with a gain after application in biomass in MPA cells of +4.3%, +1.9%, +4.5%, +5.7% for ages 2, 7, 8 and 9 respectively and <+1% for ages 3, 4, 5 and 6 which move to inshore cells before the end of the MPA. Only age 2 were protected because present alone in cells 23E5, 20E7 and 19E7 with a gain in biomass of +18.2% after the first MPA period. Although effort during MPA period is reallocated on remaining cells, no increased landings occured in no MPA cells because effort is applied on a smaller number of individuals. Rather, a slight decrease (<+1%) in landings was shown due to the variation in the *landable* proportion (33% in the MPA againt 27% outer of the MPA). MPA effect was strong for Nephrops in the only impacted 23E5 cell by the closure for this stock (+245.1% for all ages). Nevertheless, for both stocks, the impact of MPA on biomasses was minor at the horizon time in regards to the increased mesh size effect (+1.2% and +3.1% of total biomass for Nephrops and Hake respectively under 70mm/MPA scenario).

3.2 short-term effect on fleet catches

The cumulated landings per fleet per metier over the horizon simulation of 5 years in ratio to the cumulated landings of the reference scenario (Figure 5) underline species-specific responses of fleets and their metiers facing to the tested scenarios. For Hake, MPA application (i.e. scenario 70mm/MPA) led to enhanced landings for all fleets such as the french netters (metiers G1 and H1; +4.0% to 9.1%) the spanish netters targetting the Megrim and Anglerfish using BAKAnets gear and being not concerned by the MPA rule (metiers K1 and L1; +2.5% to 7.6%) and at a lesser extend the french trawlers (up to +3.1%) which had only one closed square belonging to the reproduction area

(24E4) where fish concentration occur year after year. However, spanish fleets using VHVO nets (metiers I2 and J2) and having five closed cells made exception with MPA having a strong negative effect (up to -10.6%) The balance for these fleets was negative between the loss in weight during the MPA period and the gain outer of the period. Discards are reduced during the period of MPA application in respect to the reference scenario and could explain for a part the positive effect of MPA for trawlers due to increased landings outer of the MPA period (Figures 6 and 7). However, simulation runs without the spanish VHVO net users (results not shown) showed that the positive effect of MPA on french trawlers was mainly explained by the loss in catches for spanish trawlers. MPA positive effect was enhanced (results not shown) if spanish VHVO net users were allowed to change of gears rather than reallocate effort on remaining cells of the metier (up to +8.7% for french trawlers) underlining a qualitative change in fishing pressure on the stock when spanish netters choose to focus on fewer cells. Concerning Nephrops stock, the impact of MPA on the french trawlers nephrops landings is sligthly positive for metiers D3, D4, F3 and F4 (up to +3.3%) and negative for metiers 1 and 2 (up to -2.0%). The impact of selectivity on Hake landings (i.e. 130mm/noMPA scenario) distinguished two groups: (i) a negative effect for french trawlers for all fleets and depending on metiers (fleets A to F; -14.0% to -22.0%) which are directly concerned by the increased mesh size (metiers using TTBLN and OTBLN gears). Discards are reduced mainly because catches are reduced; (ii) a positive effect for french (G and H; +5.1%) and spanish netters (I, J, K and L; +4.9%). For these last fleets, since they are not concerned by the improved selective gears rule, the positive effect is totally explained by passive gain of the trawlers loss. The impact of selectivity on Nephrops landings is strongly positive for all fleets fishing nephrops (fleets A to F) but depend also on metiers (+10.8%

to +18.9%).

3.3 long-term effect on fleet catches

Beyond the snapshot of cumulated landings at the 5-year horizon time, the dynamic aspect of the landings and the potential interaction of a combination of management rules is addressed by Figure 8. For both stocks, several groups of metiers under tested scenarios can be isolated and even if response of fleets was scenario-specific in a larger extend, dispersion of metiers for a given fleet across groups underline that effect of management scenarios equally depended on metiers. From hake landings, 3 groups of response to the tested management rules could be identified from the cluster analysis (Figure 8a): (i) For the french trawlers (Fleet A to F), the 70/100/130 mm mesh size scenarios are discriminated both by x-axis and y-axis, a higher mesh size meaning a greater immediate loss but a higher rate of gain per year (Figure 8a) since stock grow up. Further, y-axis separates MPA/noMPA scenarios and application of MPA scenarios was additional effect and led to greater rate of gain per year without effect on immediate loss and whatever the selectivity scenarios. A trawler subgroup is constituted by the metiers 1, 2, 5 and 6 which showed larger time to recovery (15 to 20 years) under the 130mm/noMPA scenario. At a lesser level, times to recovery are greater than 5-year horizon time for the other scenarios apart from the 70mm/MPA scenario for which this time is immediate, metiers having closed squares or not; Another subgroup is constituted by the metiers 3 and 4 across the fleets (i.e. whatever the vessel size) and display same features than the previous one but at a lesser scale; (ii) The french netters (fleets G and H) and spanish trawlers (fleets I, J, K and L) only fishing on Hake stock, constitute a group of metiers having no immediate loss and various rate of gain per year. Then, the balance of landings is immediately positive for these fleets. MPA scenarios led to the greater rate of gain per year for the french netters (greater than 1.0% per year for G1 and H1) not concerned by the closure. I2 and J2 metiers made exception having 5 closed squares under the MPA scenarios and had a heavily negative balance with a very high time to recovery (greater than 20 years) if mesh size was of reference.

The nephrops stock is only fished by the french trawlers (fleets A to F, metiers 1, 2, 3 and 4). Nephrops landings of these fleets could be separated into 3 groups of response (Figure 8b) across fleets depending on metiers: (i) Metiers 1 and 2 had no immediate times to recovery but mainly below the 5-years simulation horizon for all scenarios except for 70mm/MPA scenario. For these metiers, stock landings showed that an increased mesh size led to increased immediate loss and higher rate of gain per year (Figure 8c) and, at the reversal of observed on Hake stock, MPA scenarios could lead to a greater immediate loss for a same level of rate of gain per year whatever the mesh size scenario; (ii) Metiers 3 and 4 accross fleets targetting nephrops constitute 2 sub-group: one with the set of intermediate trawler metiers C3,C4, E3 and E4 with no immediate loss and positive balance depending on the scenario; another sub-group gathers large trawler metiers F3, F4, D3 and D4 with negative immediate balance and for which MPA decreased the short-term loss. For nephrops, interactions between MPA and selectivity depend on metiers.

3.4 effect on fleet revenues

The respective landing from the Nephrops and Hake stocks is integrated into the gross return of each metier and the various trends in landings between the two stocks may be solved examinating the gross return with respect to the different tested scenarios. Hence, three groups of response could be identified on Figure 8c: (i) a group with a positive gross return balance with positive rate of gain per year, (ii) a group with a lot of metiers closed to the zero immediate loss and zero rate of gain; (iii) a group with immediate loss greater than 15% associated with large time (>10 years) to recovery the reference level. The group 1 was constituted of metiers had had positive landings balance such as the french intermediate trawlers E3, E4, C3 and C4 less impacted by loss on hake landings and having gain on nephrops landings, the french netters G and H and spanish trawlers I, J, K and L. For metiers of group 1 the rate of gain per year is higher for MPA scenarios (from 1 to 2%). The group 2 was constituted of metiers 1, 2 and large trawlers D3, D4, F3 and F4 demonstrating that a loss in landings do not necessarly lead to a loss in global gross return because gross return from each stock could be balanced (For example, metiers A1, A2, B1 and B2 have positive grossreturn balance (range from 0.2 to 2.6% after 5 years because losses on Hake were balanced by gains on Nephrops for all scenarios). Price dynamic (higher price when the total landing on the attached market place decrease and reversal) had a tendency to erase difference in gross return between scenarios for these metiers. The group 3 was constituted by metiers having largely depleted landings on Hake stocks such as I2 and J2 spanish trawlers using VHVO gears whereas MPA scenarios occur, and also by the fleet-metiers with largely depleted landings on Hake stock whereas they only targetting Hake such as C5, C6, E5, E6, D5, D6, F5 and F6.

3.5 elasticity analysis

The application of multipliers on capturability or natural mortality of stocks enables to assess the degree of sensitivity of the simulation outputs to these uncertain input parameters and to evaluate if differences between metiers are kept with these other settings. Capturability changes lead to altered stock biomass (for hake for 70mm/noMPA -94.6% and +72.5% respectively for $Q = Qref \times 10$ and $Q = Qref \times 0.1$ for nephrops for 70mm/noMPA collapse to -99.8% and gain of +482.0% respectively for $Q = Qref \times 10$ and $Q = Qref \times 0.1$) which could be explained by increased or respectively decreased fleet landings (Figures 9a and b). Whatever, differences between metiers were kept and even enhanced (metiers 3 and 4 were less sensitive than metier 1, 2, 5, 6) except for metiers I2, J2 on Hake or metiers 3 and 4 on Nephrops which were greatly altered in case of 0.1*Qref simulations. Equally, stock biomasses are sensitive to the natural mortality (+21.2% with $M = Mref \times 0.8$; -17.5% with $M = Mref \times 1.2$) with the consequence of slightly increasing or respectively decreasing the time required for fleets to recovery to the reference level of Hake landings (Figure 9c).

The effect of migration on Hake trajectories of biomass and catches was quite important since pattern of catches was quite different while no Hake migration was taken into account (i.e. unabled age-specific movements between zones; reproduction and recruitment in all cells of the stock area). Higher landings occurred for all metiers of all trawlers the first semester of each year in comparison to reference simulations using the migration pattern (results not shown).

When hake is uniformly distributed on its area of presence the trawlers targetting nephrops got access to the mature age classes which were only localized on reproduction cells between January and June in the case of migration pattern. If no migration occurs, effect of MPA is reversal for trawlers and reference levels for landings take a long time to be overshooted (Figure 9d) because the higher landings with no migration particularly for metiers 3 and 4 are greatly amputed.

Applying the fishing mortality at the cell scale rather than at the zone metier scale led to greater final biomass for both stocks (+ 329.0% and + 75.2% for Nephrops and Hake respectively for the 70mm/noMPA scenario) underlining that results are scale-dependent. Indeed, in a case fishing efforts target the whole fish present in each metier area whereas in the other case efforts are assumed to be applied cell by cell creating local depletion on local fish abundance. Greater final bomass is explained by the fact that, for all fleet-metiers, landings are less important and times to recovery to the reference level are increased (Figures 10d and e). The difference between metiers observed in case of zone metier application was kept for Hake stocks comparing to the cell scale fishing mortality application. Concerning Nephrops stock, differences between metiers C1, C2, F1, F2 and C3, C4, F3, F4 are quite reduced.

4 Discussion

Because fisheries could be mixed fisheries (in the largest sense, a mixture of species and ages/stages), fishery management alternatives to TAC should be investigated to avoid by-catches, discards and overquotas of non-targetted species. Such alternatives include Marine Protected Areas which aim at protecting fish concentration from fishing i.e. either concentration of non-targetted species, immature and unmarketable individuals to let them grow and reproduce themselves, or spawning adults concentration before or during the spawning season to keep the potential production of eggs initiating the next year-class. Hence, design of MPA should depend either on spawning season which usually lead to fish concentration of adults, or on juvenile aggregation zone after the spawning (i.e. nursery). The present tested scenarios for the management of the mixed Hake/Nephrops fishery had the dual goal of limiting the spawner catches of Hake before they reproduced themselves using a closure design in space and time and limiting by-catches of juvenile Hake by altering selectivity of activities targetting Nephrops. From 2001, the emergency plan implemented by the Commission for the recovery of the Northern hake stock associate these two technical measures in addition to a TAC reduction: A 100 mm minimum mesh size implemented for trawlers (for vessel >12 meters and when hake comprises more than 20% of the total amount of marine organisms retained onboard) and two areas have been defined, one in Sub area VII and the other in Sub area VIII, where a 100 mm minimum mesh size is required for all trawlers, whatever the amount of hake caught. Using ISIS-FLR we tested first a total seasonnal closure for trawlers to simplify the respective role of MPA and gear selectivity. Hence, ISIS-FLR was showed as a tool designed to model the effect of such spatialized management rules taking into account of the spatia-temporal co-occurence between stock distributions and spatio-temporal disaggregated fishing activities. By simultaneously handling several species, the model is designed to implement rules in a mixed fisheries context using a combination of rules to attempt to solve trade-off in fishing various species.

However, these first results concerning the two tested alternative scenarios (increasing gear selectivity and implementing MPAs) are only illustrative of the current capacity of the tool and do not constitute policy recommendations since strong uncertainties exist in the conditionning of the model: (i) For nephrops, a length-structured model may be investigated to test the artificial slicing procedure in age classes which does not take account of the variability in individual growth rate and hence the variability in length-at-age. It could be also required to take into account of growth, maturity and catchability sex dependence (ICES, 2006a); (ii) For hake an underestimation of growth were underlined by tagging experiments (Bertignac and de Pontual, 2007); (iii) For selectivity ogive assessment (ICES, 2006a), analysis of nephrops selectivity data in the past often keep haul which exhibit good fit with the sigmoid selection curve model whears it sometimes represented only 50% of the total number of hauls. In addition, Briggs et al. (1999) demonstrated that vessel size affects nephrops selectivity. Finally, an alternative management rule to increased mesh size which is currently tested at Ifremer should be tested (NECESSITY, 2006). Indeed, the preliminary results from a grid device look promising and the results show clear size selection of Nephrops. This new designed gear should be tested in other fisheries to confirm these findings and provide better definition of appropriate bar spacing.

As stressed by Pelletier and Mahevas (2005) , recent models in fisheries sciences aims at taking into account of space and time distribution of the abundance of the populations and their demographic processes possibly varying in the course of life cycle of species. Further, since some demographic processes have been shown to be age-specific (e.g. migration, mortality) the population dynamic is simulated in a age-structured way. In ISIS-FLR, successive demographic processes could occur depending on relevant areas and time steps (class change, migration, reproduction, recruitment). The ISIS-FLR model as a generic tool aim at being helpful to organise age-disaggregated population data and turn out data analysis (mapping of stock abundances, etc.) for modelling population dynamics in space and time including migration patterns. On a hand, FLR provides R classes of objects to hold and structure data related to as many as stock dynamics we want to describe. Further, modularity of the FLR language was a great help to design new classes to hold more complex data to support migration patterns. Hence, the ISIS-Fish operating model and it specificity (Mahevas and Pelletier 2001) have been fully and successfully re-coded into the FLR environment. Other example of biological operating model using FLR blocks are now available (e.g. Hamon *et al.* in press on the North sea roundfish mixed fisheries) and are described on the FLR web site. The current specificity of the ISIS-FLR model is the possibility of a high level of spatio-temporal desaggegation following the grid-based unit of management that are the ICES squares. Then, in the hake/nephrops case study, age-specific migration between different locations and at various time is of great contribution to explain the variation in catches and the catches composition over time for the different fishing activities. In this case, the seasonal aggregation of spawners during the spring prevent a part of the mature population to be harvested by the trawlers either because they target nephrops and do not try to go fishing out of the nephrops stock limits or because thet cannot reach the reproduction zone from their harbour. Testing application of fishing mortalities with a cancelled hake migration pattern enabled to quantify such an effect.

In the ISIS-FLR model, stocks and fishing fleets are separately structured on the same grid-based space and time to mimic the mismatch between spatio-temporal application of the fishing effort and particular population zones in a mixed fishery context (e.g. mismatch is usually observed when a fleet either do not target only one species but rather several species at the same time, or possibly when a non-targeted stock overlaps the targeted stock, etc.). But, if the FLR environment provided blocks to handle data to build a fleet operating model, FLR classes had to be extended to reproduce this feature and organize the desagregation of effort into different fishing activities. Then, the heterogeneity of the fishing effort and vessel characteristics could be organized using ISIS-FLR as well as ISIS-Fish in separated categories described by encapsulated or linked classes of objects: several set of vessels attached to different harbors having several metiers using distinct gears for fishing an array of species in different areas depending on time. Hence, heterogeneities of catching power between set of vessels, selective ogives between metiers and finally their spatio-temporal dimension are explicitally taken into account. In particular the distangle was made between the various stock catchability specific to a given fishing activity and the stock vulnerability specific to biological features of stocks (Mahevas and Pelletier, 2004). In addition, ISIS-Fish defines strategies as subgroups of set of vessels sharing same metiers but splitting total effort over time into efforts per metier depending on different activity calendars. For example, fleet data analysis from logbooks and sales declaration for french trawlers on the hake/nephrops fishery of the Bay of Biscay (Mahevas *et al.* , 2006) led to implement in ISIS-FLR a set of two set of vessels (i.e. two vessel sizes of french trawlers) each displaying 3 strategies. In each strategy, 6 different metiers are possible depending on the spatio-temporal allocation of effort and main targetted species. Hence, conditionning ISIS-FLR model may be data-consuming since it requires finer scale data on fleets and stocks which may not be readily available (e.g. trip data to identify metiers on the main assumption that catch profiles are indicators of metiers as described in Pelletier and Ferraris 2000; tagging survey to evaluate migration coefficients between zones, etc.) and it may be more convenient to focus on model which have lower level of data disaggregation. However, do not spatialize fleet and stock data suppose some strong underlying assumptions relaxed by ISIS-FLR. Then, in ISIS-FLR populations are not homogeneously distributed in space and time but display age-disaggregated structures related to ontogenic migration patterns based on the spatio-temporal dimension of the life cycle. The fishing effort is not uniformly applied over population but heterogeneously occurs due to either various fishermen's access to the resource or various targetting behaviours. For species displaying migratory movements, models which neglect these features may goes wrong if it exists spatio-temporal heterogeneity in fishing effort.

ISIS-FLR model is a contribution to assess the effect of a space and time specificity (i.e. metiers) in the effort distribution for a given set of vessels on the stock dynamics they are fishing. But more focus is on the quantification of the possible effect of implementation of management rules on each metier evolved in the fishery. A rising consensual point of view turns fishery modelling effort toward a fleet-based management of stocks (TECTAC, 2006) and first step would be to quantify in economic terms the impact of management rules on fleet targetting these stocks as modelled here. In a second time, prediction of consequence of the possible fishermen switch of activity in response to the management constraint should be modelled to test the efficiency of the implemented recovery plan in the long run (Christensen and Raakjaer, 2006). Then, due to technical interactions in the simulated hake/nephrops fishery, no scenario led to short-term increased of landings and revenues at the same time for all implemented fleets. As a general rule, some metiers gain advantage from the loss of others. In the point of view of fleet management, the interest of such a model is to provide a tool to identify specific fleet responses to the tested management rules, quantifying interdependency effects and loss of marketable catches in a fluctuating market context (price dynamics, discount rate, etc). Following, instances of fishery management may base their choices and decisions on the stock and economic projections performed by the model. Diagnostic plots such as presented in this paper could be helpful in decisions (e.g. to identify which fleets may need subsidies if the given combination of management rules is driven, etc.). Nevertheless, three main causes of uncertainties or elasticity on simulated projections have been identified: (i) uncertainties on input data (e.g. uncertainties on stock parametrization such as initial stock number, catchability, migration, no exhaustive or error in fleet effort data, etc.); (ii) results dependent on the design of the model (e.g. scale-dependent application of fishing mortality) and (iii) fishermen behaviour retroaction (fishing effort realloaction on other zones or other activities, non-compliance, etc.). The FLR project is designed to get some insights in the first type of uncertainties using stochasticity with repeated simulation and bootstrapping (Kell *et al.*, 2007) and this underline the relevance of fully recoding ISIS-Fish into the FLR environnement and plug it with the other tools providen by FLR. As for the uncertainties inherent to the model design, ISIS-FLR have proven that these features could be investigated by various settings of the model. Fishermen response have also be investigated using ISIS-FLR under the MPA scenarios. This last point is known to greatly impact the success of management rule implementation and the most recent papers in fisheries stress on the importance of the feedback behaviour of fishermen in fisheries modelling. In particular, as we decided to perform a static allocation of effort in the present simulations, a same set of vessels could not dynamically change allocation of activity between metiers and further could not change of strategy to adapt its fishing practice to the implemented management rules.

Then, numerous simulations should be performed changing short-term effort reallocation rules to investigate the impact on results of alternative fishermen choices. Using the present design of ISIS-FLR, this could be easily done using the modular aspect of the model by creating additional new rules from existing demonstration examples.

Linking the ISIS-FLR model with the FLR project, this model acts as an entry point operating model of the closed-loop management procedure evaluation to test various management strategies (Kell *et al.*, 2007). Then, the operating model can be linked with FLR tool in current development such as the observation module that simulates data collection from the true population in the operating model; an assessment model to derive estimates of stock status from the simulated observations; and a predefined set of management actions according to some specified rules (e.g. an HCR), which takes into account the outcome of the assessment. However ISIS-FLR is able to test other regulations beyond the classical TAC and stock-based management, such as MPAs application as indirect effort regulation taking into account of economic incidence on fleets. Then, this model constitutes a fleet-based extension to the FLR environment and a proposal to be added for developing an FLR-shaped generic economic and social simulation tool (e.g. the FLEcon package in current development). Results at the metier or at the fleet level showed in the economic part of the present simulations are still preliminar and only relative landings outputs were given preventing to take into account of the fixed or variable costs for fishing. Nevertheless, the architecture to perform fleet effort optimisation depending on economic outputs, or reversal, economic outputs depending on fleet effort dynamic choice, is already done. Then ISIS-FLR constitute a modulable economic operating model that simulate the *true* population depending on various assumptions on fishing behaviours, a set of classes integrated in the FLR tool set. This model go strengthenen the FLR proposal to provide a standard open-source collection of tools suggesting a generic modelling framework for building fleet-based management strategies evaluation. A particular challenge of the ISIS-FLR model will be to test and predict the effect of fisher response behaviours on the success of the tested management options before their implementation.

5 Aknowledgement

This study was evolved in the EFIMAS project ('Operational Evaluation Tools for Fisheries Management Options') granted by the EU 6th Framework Pro-grame Specific Targeted Research Project SSP8-CT-2003-502516.

A population dynamic submodel equations

The population dynamic sub-model calls the following demographic processes for each time step inside the simulation loop:

- *class change*. Due to ageing, classe change occurs either the 1^{st} of January if the population is age-structured, or at the beginning of all time steps if a length-structured population is simulated. In this last case, the proportion of individual changing class from a step to the next is predicted from the common reversal Von Bertalanffy relation.
- *seasonal large scale ontogenic migration*. Possible age-specific migrations are simulated using coefficients which are specifically applied on the spatially distributed abundance as a proportion of migrants from an area to another.
- *reproduction*. Egg production occurs in reproduction cells from age-desagregated spawner abundance (located in reproduction cells) and fecundity-at-age in timing given by the time desagregated ogive of reproduction. From a step to the next a egg mortality is applied on the pool of egg and larva.
- *recruitment*. New recruited from the larval pool are uniformly distributed between recruitment cells in function to the timing given by the ogive of recruitment.

Hence, the stock-recruitment relationship is split up into a stock-eggs relationship and the application of an eggs natural mortality. Then, the abundance N for each stock for the next time step is given by:

$$N(t+1)_{stock,age,cell} = SR(t)_{stock,age,cell} \times \left[\left[(N(t)_{stock,age,cell} \times CC(t)) \times Mig(t)_{stock,age,cell}\right] + R(t)_{stock,age,cell}\right] \quad (A.1)$$

With CC the array of class change coefficients, R the array of new recruited, Mig the array of migration coefficients and SR the array of survival rates. All arrays are cell and time step desagregated. The survival rate give the proportion which is substracted to the population due to the mortality process. The equation A.2 is the common exponential model to compute population dynamics in fishery sciences:

$$SR(t)_{stock,age,cell} = exp[-F(t)_{stock,age,cell} + M(t)_{stock,age,cell}] \tag{A.2}$$

with F the fishing mortality computed from the exploitation model and M the natural mortality.

A Standardized effort calculation per metier

$$travelTime_{vessel,metier} = 2 \times \frac{1}{nbCells_{metier}} \sum_{i=1}^{cells \subset metierzone} distance(harbor, cell_i) \tag{A.1}$$

$$\begin{aligned} distance_{harbor,zone} = & \sum_i Rearth \\ & \times [\sin(lat.cell_i/p) \times \sin(lat.harbor/p) \\ & + (\cos(lat.cell_i/p) \times \cos(lat.harbor/p) \times \cos(lon.cell_i/p - lon.harbor/p))] \end{aligned} \tag{A.2}$$

with $Rearth = 6378.388$, the radius of the earth.

$$fishingTimePerTrip_{vessel,metier} = tripDuration_{vessel,metier} - travelTime_{vessel,metier} \tag{A.3}$$

$$nbTrip_{vessel,metier} = \frac{monthDuration - mininactdays_{vessel,metier}}{tripDuration_{vessel,metier}} \tag{A.4}$$

$$fishingTime_{vessel,metier} = fishingTimePerTrip_{vessel,metier} \times nbTrip_{vessel,metier} \tag{A.5}$$

$$stdEffortPerHour_{vessel,metier} = nbGearsPerOpe_{vessel,metier} \times nbFishOpePerDay_{vessel,metier} \tag{A.6}$$

$$stdEffortPerMetier_{vessel,metier} = fishingTime_{vessel,metier} \times stdEffortPerHour_{vessel,metier} \tag{A.7}$$

$$stdEffort_{fleet,metier} = stdEffortPerMetier_{vessel,metier} \times nbVessels_{fleet} \times activity_{metier} \tag{A.8}$$

A fishing mortalities calculation

The fleet dynamic sub-model enables to compute disaggregated fishing mortalities for each time step of the simulation loop as follows:

$$F(t)_{stock,age,cell} = \sum_{1}^{i}\sum_{1}^{j} F(t)_{fleet_i,metier_j,stock,age,cell} \tag{A.1}$$

The fishing mortality per fleet per metier $F(t)_{fleet,metier,stock,age,cell}$ is performed as described in the following equation:

$$\begin{aligned} F(t)_{fleet,metier,stock,age,cell} = & E(t)_{fleet,metier,cell} \times tgtFctr_{fleet,metier,stock} \\ & \times sel_{metier,gear,stock,age} \times q_{stock,age,season,cell} \end{aligned} \tag{A.2}$$

with:

(1) $E(t)_{fleet,metier,cell}$ the effort per metier as a part of the total fleet effort dedicated to this metier. As detailed in Appendix B, fishing effort per metier is explicitely performed in the model by predicting the fishing time depending on the number of possible trips per time step (e.g. a month), the type of trips (e.g. 5 days at sea:2 days of inactivity, versus 5 × 1 days at sea::2days of inactivity) and taking into account of the travel time to reach the targetted fishing cells for this metier from its specific harbor. then, fishing time is standardized per metier taking into account of the gear efficiency ('standard factor'of gears) and the number of fishing operations per day. Finally, effort per metier is computed from the number of vessels belonging to the strategy (f̃leet) and the percent of time activity spent in this metier for this time step.

(2) $tgtFctr_{fleet,metier,stock}$ a stock-specific target factor per metier. This coefficient aim at taking into account of the relative efficiency of a unit of effort between metiers (obtained by performing a Generalized Linear Model on

CPUEs; details in Mahevas and Pelletier (2004)) measuring the degree of linkage of the metier with each of the species caught.

(3) $sel_{metier,gear,stock}$ gear selectivity computed from a selectivity model for the gear used by metiers.

(4) $q_{stock,age,season,cell}$ disaggregated stock-specific catchability coefficients per age per zone displaying a seasonal pattern. Since a target factor related to gear used by metiers having previously been defined, it should be noted that the catchability parameter of the population model is only dependent on stock availability rather than a mixture of stock availability and of fishers technical efficiency at catching the species.

A Related-economic equations

$$price_{fleet,metier,stock} = \alpha_{market} TotalLandings_{stock,market}^{\beta_{market}} \tag{A.1}$$

$$GrossReturn_{fleet,metier} = \sum_{1}^{nbStocks} [Price_{fleet,metier,stock} \times Landings_{fleet,metier,stock}] \tag{A.2}$$

$$GrossReturn_{fleet,metier} = GrossReturn_{fleet,metier} + [Effort_{fleet,metier} \times GrossReturnFromOtherSpecies] \tag{A.3}$$

$$GrossReturnFromOtherSpecies = \frac{[GrossReturn_{allSpecies}(t0) - GrossReturn_{simulatedSpecies}(t0)]}{Effort_{fleet,metier}(t0)} \tag{A.4}$$

$$NetRevenue_{fleet,metier} = (1 - LandingCost_{fleet,metier}) \times GrossReturn_{fleet,metier,stock} \tag{A.5}$$

$$SharedCost_{fleet,metier} = (FuelCost + BaitCost + IceCost + FoodCost) \times Effort_{fleet,metier} \tag{A.6}$$

$$ReturnToBeShared_{fleet,metier} = NetRevenue_{fleet,metier} - SharedCost_{fleet,metier} \tag{A.7}$$

$$CrewShare_{fleet,metier} = CrewShareRate_{fleet,metier} \times ReturnToBeShared_{fleet,metier} \tag{A.8}$$

$$GrossWage_{fleet,metier} = \frac{CrewShare_{fleet,metier}}{CrewSize_{fleet,metier}} \tag{A.9}$$

$$NetCrewShare_{fleet,metier} = CrewShare_{fleet,metier} - [InsuranceCost_{metier} \times CrewSize_{fleet,metier}] \tag{A.10}$$

$$VesselShare_{fleet,metier} = (1 - CrewShareRate_{fleet,metier}) \times ReturnToBeShared_{fleet,metier} \tag{A.11}$$

$$OwnerMargin_{fleet,metier} = VesselShare_{fleet,metier} - OtherVariableCosts_{fleet,metier} \times Effort_{fleet,metier} \tag{A.12}$$

$$GrossSurplus_{fleet} = \sum_{metierinM_{fleet}} (OwnerMargin_{fleet,metier} - LicenceCost_{fleet,metier} - ovec_{fleet}) \tag{A.13}$$

$$ReturnFromOtherSpecies = \frac{ReturnToBeShared_{otherSpecies}(t0)}{Effort_{fleet,metier}(t0)} \tag{A.14}$$

$$ReturnToBeShared_{fleet,metier,otherspecies}(t) = ReturnFromOtherSpecies \times Effort_{fleet,metier}(t) \tag{A.15}$$

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