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Evaluation of the bioeconomic sustainability of multi-species multi-fleet fisheries under a wide range of policy options using ISIS-Fish

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Abstract:

In order to provide reliable scientific advice and support for fisheries management, it is necessary to evaluate the biological and economic sustainability of complex fisheries, such as multi-species multi-fleet fisheries. Existing policy-screening modelling tools are not fully suitable in this purpose due to either an over-simplified description of population dynamics, or due to the lack of consideration of economic aspects.

In this paper, we present a package that enables quantitative bioeconomic assessment of management scenarios. Population dynamics is described through spatially- and seasonally-explicit models. Exploitation dynamics is characterized by several fishing activities with specific spatial and seasonal features, and practiced by several kinds of vessels with specific technical characteristics. Exploitation costs and revenues are considered at several levels: the fishing trip, the fishing unit (vessel and crew), and the vessel owner. The model is generic and can be used for different types of fisheries. A database is attached to the software for the storage and updating of information for each fishery. This includes the specification of model dimensions and of the parameters describing populations and exploitation. Several model assumptions regarding either population or exploitation may be adapted to suit a specific fishery. Both policies and corresponding fishers' response may be interactively specified through JAVA™ scripts. This version of ISIS-Fish allows for the calculation of biological and economic consequences of a range of policies, including conventional ones like catch and effort controls, and alternative policies such as marine protected areas. To facilitate policy-screening in a high-dimension parameter space, the software includes features, like interfaces for sensitivity analysis and simulation queues.

Keywords: Simulation tool; Complex systems; Population dynamics; Bioeconomic model; Fisheries dynamics; Natural resource management; Policy-screening

1. Introduction

Most fisheries are complex systems due to the range of species exploited and the variety of fishing activities targetting them. These multi-species multi-fleet fisheries (also termed mixed fisheries) form the majority of fisheries across the world, in particular in coastal areas and on continental shelves. Many coastal communities rely on the existence of such fisheries either for subsistence or commercial purposes, in general for both. Coastal areas are subject to increasing demographic pressure, and they host activities other than fisheries. Reversing loss of environmental resources while integrating principles of sustainable development is a challenge for the forthcoming years, as e.g. stated in the Millenium Goals (http://www.un.org/milleniumgoals). This requires identifying the management options that ensure fisheries biological and economic sustainability while satisfying constraints linked to other uses. This can be achieved by exploring the consequences of policies using e.g. simulation models of fisheries dynamics. Marine Protected Areas (MPA), including among other regulatory measures any restriction of fishing over space (and possibly time), constitute a key policy for the management of coastal fisheries and ecosystems, because zoning of uses is often indispensable to achieve a range of conflicting goals such as biodiversity conservation, sustainable development of economic activities, including fisheries.

There are few published models in fisheries science that enable to explore a wide range of management options including MPAs (see the review by Pelletier and Mahévas (2005)). For many models, the description of population dynamics and exploitation dynamics is not appropriate neither for investigating MPA design, nor for exploring mixed fisheries issues. Mahévas and Pelletier (2004) presented ISIS-Fish, a simulation tool for evaluating the impact of management measures on fisheries dynamics (ISIS-Fish 1.0), while Pelletier and Mahévas (2005) presented, among other things, version 1.5 of ISIS-Fish. In these versions, ISIS-Fish does not consider the economic viability of the fisheries, and investigations only rely on simulations of abundance, catch and effort trajectories under a range of policy options. However, it is important to appraise economic consequences of management scenarios, as a policy may be beneficial for resource status, but not economically viable. This is particularly true for MPAs where previous theoretical models have shown that it may be difficult in the case of no-take zones to establish conditions that guarantee a double payoff, i.e. an increase in both yield and biomass (Sanchirico and Wilen 2001a; Boncoeur et al. 2002).

In this paper, we present version 3.0 of ISIS-Fish which encompasses a large number of new developments in the software and underlying model. Most importantly, this version contains a bioeconomic model of fisheries dynamics that enables the assessment of economic consequences of policy options and to calculate economic indicators of fisheries status and dynamics. By bioeconomic model, we mean a fisheries model that incorporates economic parameters or variables, either as forcing variables or endogeneous variables (i.e. variables with their own dynamics in the model). We could not find in the literature any other generic spatially-explicit bioeconomic model for quantitative assessment of fisheries management policies.

2. Model description

In the present paper, we briefly review the features existing in version 1.0 of ISIS-Fish presented in Mahévas and Pelletier (2004), and we mostly describe the new model developed to address economic issues, as well as the numerous new features introduced in the population model. The introduction of an economic component in ISIS-Fish resulted in comprehensive changes in the exploitation model where costs are now detailed (see subsection 2.2). The new parameters and variables defined in this model may be used to code fishers' behaviours that depend on economic conditions. (C)

(A) The ISIS-Fish fishery model is a deterministic dynamic simulation model. It is time-discrete with a monthly time-step.

The ISIS-Fish fishery model relies on three interacting submodels respectively pertaining to population, exploitation, and management. These interactions take place within the fishery area that is a spatially discrete mapping to a regular grid. The grid serves to define zones for each population, fishing activity and management measure. Defining the fishery area and the grid resolution is a first and important step in parameterizing an application of ISIS-Fish. It allows specifying zones that can then be used as population, exploitation or management zones. Note that all zones are independent from one another. At any time step (month), fisheries dynamics is determined by the extent of the spatial overlap (in cells) between population zones, fishing activity zones and management zones.

ISIS-Fish relies on an object-oriented modelling approach. The static model underlying ISIS-Fish may be represented with a class diagram (Figure 1) that depicts model objects and the relationships between them. In ISIS-Fish, objects are natural objects of the fisheries system. Object attributes are listed in Table 1.

2.1. Population dynamics

For many fish populations, seasonal and spatial variations in population abundance, are dictated by large-scale ontogenic migrations such as migrations of spawners for reproduction, and migrations linked to habitat preferences such as nurseries or feeding areas. In the model, population zones and seasons are defined according to the timing and spatial patterns due to biological processes such as migrations, growth, reproduction and recruitment. Population dynamics is either stage- , length- or age-structured. ((B)).

Although the model primarily focuses on complex dynamics inherent to mixed fisheries, such as interactions between fleets and incidental catch, it is sometimes necessary to account in addition for inter-specific relationships, e.g. predator-prey relationships between species. This feature was introduced in the present version as follows: the natural mortality coefficient and the reproduction function of a given population can be made dependent on the abundance of another population, which allows for the inclusion of predation and cannibalism.

Class- and zone-specific abundances of a given population at the beginning of month *t* are denoted :

(1) $$^{t}\mathrm{N}(t) = \left(N(t, zpop_1), \ldots, N(t, zpop_j), \ldots N(t, zpop_n)\right)$$

where $^{t}\mathrm{N}(t)$ is the transpose of $\mathrm{N}(t)$, $N(t, zpop)$ is the row vector $\left(N(t,c,zpop), c = 1,\ldots, NbClass\right)$, and *c, zpop, NbClass* and *n* respectively denote a population class, a population zone, the number of classes and the number of zones of the population.

Change of class, migrations, spawning and recruitment are assumed to occur instantaneously, and following this order, at the beginning of the time step, whereas natural and fishing mortalities affect population abundance throughout each time step. Survival rates follow the classical exponential decay model widely used in fisheries models, so that the survival rate of class *c* at time *t* in population zone $zpop$ is :

(2) $$sr(c, zpop, t) = \exp\left(-\left(F(c, zpop, t) + M(c)/12\right)\right),$$

where $F(c, zpop, t)$ and $M(c)$ respectively denote the instantaneous fishing mortality rate of class *c* in zone $zpop$ at time *t*, and the instantaneous natural mortality rate of class *c*. In Eq. (2), fishing mortality is expressed in month^{-1}, while natural mortality is in year^{-1}. Natural mortality may be made dependent on zones or seasons through an equation. Fishing mortality is computed from fishing effort (see § 2.2). Survival rates are arranged into a diagonal matrix **SR(t)**.

From the chronology of processes, the evolution of population abundance between *t* and *t+1* can be written as :

(3) $$\mathbf{N(t+1)} = \mathbf{SR}(\mathbf{t})\Big(\underbrace{\mathbf{R(t)} + \mathbf{D}^{\mathbf{mig}}_{\mathbf{season}}\mathbf{CC}_{\mathbf{season}}\mathbf{N(t)} + \mathbf{N}^{\mathbf{immig}}_{\mathbf{season}}}_{\mathbf{N^{*}(t)}}\Big),$$

where **R(t)** is the recruitment vector, $\mathbf{D}^{\mathbf{mig}}_{\mathbf{season}}$ is the migration matrix, $\mathbf{N}^{\mathbf{immig}}_{\mathbf{season}}$ is the immigration vector, and $\mathbf{CC}_{\mathbf{season}}$ is the matrix depicting change of class due to aging in the case of an age-structured model, and to individual growth in the case of a stage-structured model. Equations corresponding to biological processes are summarized in Appendix 1. Equation (3) is simplified if not all demographic processes occur at time *t*.

Similarly, population biomass at time *t* may be calculated from $\mathbf{B(t)} = \mathbf{W} \circ \mathbf{N}(\mathbf{t})$, where **W** is the vector of mean weight of class ***c***, possibly specific to population zones, and "$\circ$" denotes a scalar multiplication between **W** and **N(t)**.

Population classes may correspond to length, sex, maturity classes or combined classes. In order to increase flexibility in model assumptions, several model parameters which were fixed in previous versions have been changed to equations, such as mean weight, natural mortality, and migration. Besides, the reproduction and recruitment model has been changed to allowing for the consideration of metapopulation structures and a variety of larval dispersion and settlement schemes (see Appendix 1).

Every parameter of the population model can be easily input through an appropriate user interface. Because most model objects are natural objects of the fishery (Figure 1), all model parameters are attributes of these objects (Table 2). Note that these parameters may be fixed (integer, boolean, real or character) or they may themselves be equations.

The only economic parameter related to populations is a price per kg for each population class. In the course of simulations, this price may possibly be affected by certain economic factors through appropriate coding of fisher's response (see § 2.4).

2.2. Exploitation model

The exploitation model of ISIS-Fish version 1.0 was extensively modified to accommodate for computation of cost and revenues. In this section, we describe model choices in relation to economic considerations. Model parameters are defined in Table 3 (see also Figure 1 for relationships between objects and Table 1 for object attributes). Exploitation is modeled through fishing effort which is a function of the number and characteristics of the vessels in the fishery, and of the fishing activities they practice (called metiers).

With respect to vessels, the model considers vessel types that group vessels with similar technical characteristics, e.g. length, tonnage, engine power (Table 3). Depending on metier, a minimum crew size is needed to operate a given vessel type. In addition to distance travelled between port and fishing grounds, fuel costs of travelling are also related to vessel type as vessel speed mainly depends on engine power and vessel dimensions. We thus assume that all vessels of a given vessel type share similar unit fuel costs irrespective of their port, because this is mostly tied to vessel characteristics. Vessel type determines the maximum duration of a fishing trip in relation with fuel autonomy. Possible trip types for each vessel type are then deduced from existing trip types. Activity range (in km) from the port may be computed from speed and maximum trip duration. It is not used in the core equations of the model, but may serve as a parameter for modelling short-term fisher's behaviour (see § 2.4). Sets of vessels are groups of vessels with similar characteristics (i.e. from a given vessel type) that originate from a given port. They enable considering specific costs per port.

The second component of fishing effort pertains to the fishing activities practiced by vessels. At the monthly scale, this is captured by the metier, which is characterized by the use of a single fishing gear. It targets a range of species among the ones that can be caught by the gear. The metier takes place in a particular metier zone which may change according to seasons, as well as the way species are targeted. This induces changes in travelling costs between port and fishing grounds. There are no costs directly associated to gears and metiers, since these depend on the vessels that engage in a specific metier. Calculation of fishing mortality strongly depends on the metiers practiced , as these determine the impact of fishing on populations via the target factor, gear selectivity, metier zones and metier season (§ 2.2.5). With regard to version 1.0, the target factor has been changed to an equation to allow e.g. for size-specific targetting for a given species.

At the yearly scale, fishing vessels practice several metiers depending on seasonal variations in resource availability, environmental and market conditions. Fishing habits and fisher's behaviour also determine seasonal changes in fishing activity. For this purpose, effort components related to metiers and vessels are linked through strategies. Strategies are sets of vessels which resort to the same sequence of metiers throughout the year, and thus strategy definition captures seasonal patterns of exploitation. Within a strategy, trip duration may change from one month to the other, as well as the number of inactivity days, allowing for possible periods of low activity. Fisher's behaviour is specified at strategy level.

Following on, fishing effort and corresponding costs are calculated in several steps. Unlike Mahévas and Pelletier (2004), we do not use a matrix notation for describing fishing effort. Notations used in the equations below are defined in Table 5. In the equations and in Table 5, the indices *cell, cl, gear, month, pop, port, sov, str, vt, zmet* and *zpop* respectively correspond to a grid cell, a population class, a gear, a month, a population, a port, a set of vessels, a strategy, a vessel type, a metier zone, and a population zone. *t* denotes a time step of the simulation, while *month* denotes the month corresponding to *t*. The *month* notation is used to index parameters that are defined at month scale, but similar across years, whereas *t* indicates quantities that may also vary across years, e.g. as a consequence of fisher's behaviour and/or management measure.

2.2.1. Fishing time per vessel and associated costs.

The first component of fishing effort is fishing time. On the one hand, it depends on trip duration (in days) which is accounted for by the Trip type object (Table 4). At any time step of the simulation, all trips in a given strategy are assumed to have the same duration, thus the number of trips per month depends on month duration and on trip duration for the vessels of the strategy :

(4) $$NbTrips(str,t) = \mathrm{Int}\left(\frac{Duration(month)\ \text{-}\ MinNbInactDays(str,t)}{TripDuration(str,t) + MinTimeBetweenTrips(str,t)}\right),$$

where for this strategy at that month, $MinTimeBetweenTrips(str,t)$ is the minimum time needed at port for supply, crew change or crew rest between trips, and $MinNbInactDays(str,t)$ is a minimum number of inactivity days, that enables considering monthly variations in overall activity, e.g. due to vacation time, vessel repair and maintenance, or bad weather conditions.

The effective number of days at port during the month is then calculated as :

(5) $$\begin{aligned} NbInactDays(str,t) &= Duration(month) - NbTrips(str,t)\,TripDuration(str,t) \\ &= NbTrips(str,t)\,MinTimeBetweenTrips(str,t) + MinInactDays(str,t) \end{aligned},$$

On the other hand, fishing time is a function of travelling time which depends on both vessel port and distance between the fishing ground of the metier practiced (called the metier zone):

$$D_{km}(port,zmet) = \frac{1}{NbCells(zmet)} \sum_{i=1}^{NbCells(zmet)} D_{km}\left(cell_{port}, cell^{i}_{zmet}\right),$$

where $D_{km}(cell_1, cell_2)$ is the distance between the centres of two cells (in km).

For each trip of month *t*, the time taken by a vessel of set of vessel *sov* practicing metier *met* to travel to and from metier zone *zmet* is expressed (in hours) as:

(6) $$TravelTimePerTrip(sov,met,t) = 2D_{km}(port,zmet)/Speed(vt),$$

At a given time step, fishing time per trip (in hours) for a vessel of strategy *str* that practices metier *met* is calculated from Eq. (6) as:

(7) $$FishingTimePerTrip(str,met,t) = 24TripDuration(str,month) - TravelTimePerTrip(sov,met,t),$$

Note that travelling time between fishing operations is ignored. Assuming that the fisher practices a single metier during the month, the overall fishing time of a vessel of strategy *str* in the month *t* follows from Eqs. (4) and (7) :

(8) $$FishingTime(str,met,t) = NbTrips(str,t)\,FishingTimePerTrip(str,met,t),$$

Similarly, the overall travelling time of a vessel of strategy *str* in the month *t* is calculated as:

(9) $$TravelTime(str,met,t) = NbTrips(str,t)\,TravelTimePerTrip(sov,met,t)$$

Travelling to and from metier zone induces metier-specific costs calculated as :

(10) $$FuelCostsTravel(str,met,t) = TravelTime(sov,met,t)\,UnitFuelCostsTravel(vt)$$

Unit fuel costs of travel are assumed to depend solely on vessel characteristics.

Fuel costs of fishing are proportional to the number of fishing operations achieved by the vessel during the month:

(11) $$FuelCostsFishing(str,met,t) = \\ FishingTime(str,met,t)\,NbOpePerDay(sov,met)\,UnitFuelCostsFishing(sov,met)/24$$

Overall fuel costs per vessel are then given by :

(12) $$FuelCosts(str,met,t) = FuelCostTravel(str,met,t) + FuelCostFishing(str,met,t)$$

Fishing also induces additional running costs that are proportional to fishing time, and dependent on the metier e.g. bait and ice costs, and crew food costs:

(13) $$OtherRunningCosts(str,met,t) = FishingTime(str,met,t)\,OtherRunningCostsPerDay(sov,met)/24$$

Costs in Eqs. (12) and (13) are per vessel and correspond to variable costs, i.e. they are proportional to some measure of effort, either in time or in number of fishing operations. In contrast, fixed costs comprise all costs that are not proportional to fishing time or fishing effort and have been payed out in order to allow vessels of the strategy to operate during a given month, for instance, administration costs, insurance costs, costs linked to port services, and possible costs of land-based equipment. In the model, fixed costs are accounted for at the year scale in order to calculate margins (Eq. (33). At the month scale, most variable costs are assumed to be shared between the vessel owner and the crew, which corresponds to the case of many fisheries:

(14) $$SharedCosts(str,met,t) = FuelCosts(str,met,t) + OtherRunningCosts(str,met,t)$$

Other costs are not borne by the crew, like costs associated to buying and maintaining fishing gears. Cost of buying gears are considered as investment costs, and are not explicitly modeled. Costs associated to repair and maintenance of gears are variable costs and are calculated for each vessel of the set of vessel ***SOV*** as:

(15) $$GearMaintenanceCosts(str,met,t) = \\ FishingTime(str,met,t)\,GearMaintenanceCostsPerDay(sov,met)/24$$

2.2.2. Standardized fishing effort per vessel

To the exception of single species trawl fisheries, fishing time on its own generally provides a poor proxy to fishing effort. In addition, the variety of metiers used in a mixed fishery makes it necessary to standardize fishing effort among fishing gears, and to account for metier-specific parameters such as the number of gears used in a given fishing operation, and the number of fishing operations per day. Making these effort components explicit enables one to capture mixed fisheries aspects and to investigate management measures that are tailored to particular gears or metiers.

For a vessel from a given set of vessels practicing a given metier, a standardized fishing effort per unit of fishing time is calculated as :

$$\begin{aligned} &StdEffortPerHour\left(sov,met,t\right)= \\ &SF_{std}\left(gear\right)NbFishOpePerDay\left(sov,met,t\right)NbGearsPerOpe\left(sov,met,t\right)/24 \end{aligned} \tag{16}$$

where $StdEffortPerHour\left(sov,met,t\right)$ is expressed in standard unit effort per hour spent fishing. The standardisation factor $SF_{std}(gear)$ (Table 5) is one for the reference gear of the fishery. Standardized effort depends on time as $NbFishOpePerDay\left(sov,met,t\right)$ and $NbGearsPerOpe\left(sov,met,t\right)$ (Table 5) could both be altered by a management measure or by fisher's behaviour.

2.2.3. Overall fishing effort per strategy

Overall standardized effort of the month is first calculated for each vessel of strategy *str* :

$$StdEffortPerVessel\left(str,met,t\right)=FishingTime\left(str,met,t\right)StdEffortPerHour\left(sov,met,t\right) \tag{17}$$

This effort accounts for fishing time, but not for travelling time (calculated in Eq. (9)).

Under the assumption of all vessels being identical in a given strategy, the number of vessels in the strategy that practice a given metier at t depends on the number of vessels in the strategy, and on the seasonal distribution of effort among metiers in the strategy. This writes:

$$\begin{aligned} &NbVesselsStrMet\left(str,met,month\right)= \\ &PropNbVessels\left(str,sov\right)NbVessels(sov)PropMetStr\left(str,met,month\right) \end{aligned} \tag{18}$$

where $PropMetStr\left(str,met,month\right)$ is the proportion of vessels practicing a metier during a month in a given strategy (equivalent in this model to the proportion of effort allocated by each vessel to a given metier during a given month), and $PropNbVesselsStr\left(str,sov\right)$ is the proportion of vessels of set of vessel *sov* in strategy *str* (Table 5).

The overall standardized fishing effort of the strategy is then :

$$StdEffort\left(str,met,t\right)=NbVesselsStrMet\left(str,met,month\right)StdEffortPerVessel\left(str,met,t\right) \tag{19}$$

2.2.4. Spatial allocation of fishing effort

Fishing effort in Eq. (19) is allocated in the metier zone *zmet* of metier *met*. Since metier zones and fish populations zones are independently defined, they may partially overlap. The fishing mortality induced by fishing effort must account for the extent of this spatial overlap. For this purpose, fishing effort per cell in the metier zone is computed under the assumption of a uniform distribution of effort over the metier zone, all cells being identical:

$$StdEffortPerCell\left(str,met,t\right)=StdEffort\left(str,met,t\right)/NbCells\left(zmet\right)$$

and we further assume that fishing effort in the overlapping area is distributed over the entire population zone intersecting this area:

$$StdEffortZpop\left(str,met,zpop,t\right)=StdEffortPerCell\left(str,met,t\right)NbCells\left(zpop\cap zmet\right) \tag{20}$$

This amounts to assuming that population abundance instantaneously redistributes over all the current population zone. The implications of these assumptions for model parameterization are further discussed in Pelletier and Mahévas (2005).

2.2.5. Fishing mortality

The fishing mortality that affects a given population *pop* as a result of fishing effort in Eq. (20) is calculated for each class *cl* of the population *pop* as :

(21) $$F_{str}^{met}\left(str, met, pop, cl, zpop, t\right) = Sel\left(gear, pop, cl\right) q\left(pop, cl, zpop, month\right)$$
$$TargetF\left(met, pop, cl, month\right) StdEffortZpop\left(str, met, zpop, t\right)$$

Fishing mortality thus depends on three additional parameters: catchability $q\left(pop, cl, zpop, month\right)$, gear selectivity *Sel(gear, pop, cl)*, and the target factor *TargetF(met,pop,cl, month)*.

Catchability is the probability that a fish present in the exploitation zone be caught by a standard unit of effort made from a non selective gear, consistently with Seber (1989)'s definition. Thus the model distinguishes between gear-dependent selectivity and gear-independent catchability. Catchability may change during the year due to particular behaviour or to seasonal concentrations of particular population stages in particular habitats, e.g. for spawning or wintering. These preferential habitats being generally small compared to the distribution area of the population, fish concentrate in space, resulting in increased fishing mortalities. The catchability model in ISIS-Fish is such that changes in catchability due to these concentration effects are consistent between stages, zones and seasons (see Pelletier and Mahévas (2005)).

The target factor measures the strength with which the population is targeted by the metier. It is necessary to distinguish between i) the impacts of a metier on its target species and on bycatch species; and ii) the catches of a given species induced by two metiers fishing in the same zone at the same time. These differences are tied to the attractivity of the species for the fisher, and they include the technical savoir-faire of the fishers resulting in fine tuning of gears, e.g. rigging, precise positioning of gears, which are not captured by gear parameters, nor by the spatial resolution of the model.

Note that in the following equations the *pop* dimension is omitted for sake of being concise. The overall fishing mortality endured by the population during the month is simply calculated by summing over strategies and metiers :

(22) $$F\left(cl, zpop, t\right) = \sum_{strategies} \sum_{metiers} F_{str}^{met}\left(str, met, cl, zpop, t\right)$$

Each population present in an area that overlaps a metier zone is subject to fishing mortality from this metier, provided that target factor and selectivity for this population are not zero. The model is thus particularly appropriate to address issues of incidental catch and their economic consequences.

2.2.6. Calculation of catch and landings.

The overall catch rate at time *t* for *cl* and *pop* in zone *zpop* is computed using the classical catch equation :

(23) $$CR\left(cl, zpop, t\right) = \frac{F}{F + M_{month}}\left(1 - \exp\left(-\left(F + M_{month}\right)\right)\right),$$

where $F = F\left(cl, zpop, t\right)$ is given by Eq. (22) and $M_{month} = M\left(cl\right)/12$ is the natural mortality for class *cl* of population *pop* during month *t*.

Corresponding catch is then obtained by :

(24) $$C\left(cl, zpop, t\right) = CR\left(cl, zpop, t\right) N^{*}\left(cl, zpop, t\right),$$

where $N^{*}\left(cl, zpop, t\right)$ corresponds to the abundance of class *cl* of *pop* in zone *zpop* at time *t* , once processes such as change of class, migration, reproduction and recruitment have been taken into account (see Eq. (3)).

Catch per strategy and metier is calculated as :

(25) $$C\left(str,met,cl,zpop,t\right)=\frac{F_{str}^{met}}{F}CR\left(cl,zpop,t\right)N^{*}\left(cl,zpop,t\right),$$

where $F_{str}^{met}=F\left(str,met,cl,zpop,t\right)$, $F=F\left(cl,zpop,t\right)$, and $CR\left(cl,zpop,t\right)$ is given by Eq. (23).

Catch is summed over zones and expressed in weight as :

(26) $$CW\left(str,met,cl,t\right)=\sum_{zones}C\left(str,met,cl,zpop,t\right)W\left(pop,cl,zpop\right),$$

Possible discards are modelled as :

(27) $$DiscW\left(str,met,cl,t\right)=DiscRate\left(str,met,pop,cl,t\right)\sum_{zpop}CW\left(str,met,cl,zpop,t\right),$$

where $DiscRate\left(str,met,pop,cl,t\right)$ represents a discarding behaviour, which may either be an intrinsic component of the strategy behaviour, e.g. a highgrading behaviour leading to discard of low value species when higher value species happen to be caught, or which may be due to the implementation of a management measure, e.g. a minimal size for catch. Foregone value of discarded catch may be calculated using species price. Hence, $DiscRate\left(str,met,pop,cl,t\right)$ is calculated from a function that is freely specified by the user (see §2.4). A survival rate of the discards may also be considered (not indicated in Eq. (27)).

For each metier in a given strategy, landings in tonnage and in gross value are then respectively given by :

(28) $$Landings\left(str,met,pop,t\right)=\sum_{classes}\left(CW\left(str,met,cl,t\right)-DiscW\left(str,met,cl,t\right)\right)$$

$$GrossValueLandings\left(str,met,pop,t\right)=\sum_{classes}Price\left(pop,cl,t\right)\left(CW\left(str,met,cl,t\right)-DiscW\left(str,met,cl,t\right)\right),$$

where $Price\left(pop,cl,t\right)$ may be calculated from a price formation function that is freely specified by the user (see § 2.4).

The net value of landings for each resource (each population) is simply derived by accounting for landing costs :

(29) $$NetValueLandings\left(str,met,pop,t\right)=GrossValueLandings\left(str,met,pop,t\right)\left(1-LandingCostRate\left(str,met\right)\right)$$

All vessels being identical in a given strategy, the net value of landings per vessel and per population is:

(30) $$NetValueLandingsPerVessel\left(str,met,pop,t\right)=\frac{NetValueLandings\left(str,met,pop,t\right)}{NbVesselsStrMet\left(str,met,month\right)},$$

where $NbVesselsStrMet\left(str,met,month\right)$ is given by Eq. (18).

2.2.7. Revenues per strategy for each metier

For a given vessel in a strategy, revenues are calculated over all populations caught by the metier. Some populations are explicitly modelled and contribute to revenue through the above equations, while other species not modelled may also contribute to the metier revenue, through a fixed term *OtherSpeciesGrossValue(str,met)* (Table 5).

The net revenue to share per vessel is then:

(31) $$NetRevenue\left(str,met,t\right)=\sum_{populations}NetValueLandings\left(str,met,pop,t\right)+\left(1-LandingCostRate\left(str,met\right)\right)OtherSpeciesGrossValue\left(str,met\right)-SharedCosts\left(str,met,t\right)$$

where the sum is taken over all populations caught by the metier, and $\mathit{SharedCosts}(str, met, t)$ is given by Eq. (14).
The crew share writes :

$$\mathit{CrewShare}(str,met,t) = \mathit{NetRevenue}_{str}^{met}(str, met, t)\mathit{CrewShareRate}(sov, met) \tag{32}$$

Net revenue (Eq. (31)) and crew share (Eq. (32)), together with gear maintenance costs (Eq. (15)) allow to compute monthly margins over variable costs for each metier:

$$\begin{aligned} &\mathit{VesselMarginPerVessel}(str,met,t) = \mathit{NetRevenue}_{str}^{met}(str, met, t) - \mathit{GearMaintenanceCosts}(str, met, t) \\ &\mathit{OwnerMarginPerVessel}(str,met,t) = \mathit{VesselMarginPerVessel}(str,met,t) - \mathit{CrewShare}(str, met, t) \end{aligned} \tag{33}$$

Under the assumption of all vessels being identical in a given strategy, margins are evaluated at the scale of the strategy:

$$\begin{aligned} &\mathit{VesselMarginPerMet}(str,met,t) = \mathit{NbVesselsStrMet(str,met,month)}\mathit{VesselMarginPerVessel}(str,t) \\ &\mathit{OwnerMarginPerMet}(str,met,t) = \mathit{NbVesselsStrMet(str,met,month)}\mathit{OwnerMarginPerVessel}(str,t) \end{aligned} \tag{34}$$

Overall margins per strategy are then obtained by aggregating previous values over the metiers practiced:

$$\begin{aligned} &\mathit{VesselMargin}(str,t) = \sum_{metiers} \mathit{VesselMarginPerMet}(str,met,t) \\ &\mathit{OwnerMargin}(str,t) = \sum_{metiers} \mathit{OwnerMarginPerMet}(str,met,t) \end{aligned} \tag{35}$$

where the sum is taken over all possible metiers of the strategy. These indices quantify the short-term profitability of belonging to the fishery for a vessel of strategy *str* at month *t*.
The overall profitability of the fishery at time *t* is calculated as:

$$\begin{aligned} &\mathit{OverallVesselMargin}(t) = \sum_{strategies} \mathit{VesselMarginPerMet}(str,t) \\ &\mathit{OverallOwnerMargin}(t) = \sum_{strategies} \mathit{OwnerMarginPerMet}(str,t) \end{aligned} \tag{36}$$

Economic margins and profitabilities at the year scale are calculated in § 2.5.2.

2.3. Management model

In ISIS-Fish, policy parameterization was designed to evaluate and compare the consequences of a wide range of management options on the dynamics of a mixed fishery. Policies considered include catch quotas (Total Allowable Catch (TAC)), direct effort control (licenses, trip limitations), gear restrictions, and MPA. Policies may be combined as far as they are compatible.
Indeed, the model being spatially-explicit with a monthly time step, it may be used to investigate policies that are permanent or temporary, and that apply either to the whole fishery area or within a particular zone. Moreover, the exploitation model makes it possible to accommodate for policies aimed at particular gears, metiers, fleets or strategies.
Each policy is described by the zone where it applies (management zone), by starting and ending months (management season), and by the years of application. Depending on the policy, additional parameters may be specified, e.g. for a TAC, the TAC level for the population concerned, the metier at stake for a metier-specific closure, etc. The description of any policy makes explicit the conditions under which the policy becomes effective, e.g. starting month. In the case of a TAC, landing the species is forbidden when cumulated landings since the beginning of the year reach the TAC value for the species.
Upon becoming effective, a policy constrains exploitation, which leads fishing units (i.e. fishing vessel and fishing crew) to adapt their fishing effort in response to the constraints. These changes are here termed « fishers' response to management ». Accounting for this response permits a more realistic assessment of the impact of a policy on both resources and fishing activities. A policy will impact any metier whose fishing zone intersects the management zone, possibly depending on the gear used by

the metier. Fishers' response may depend on their fishing habits reflected by the strategy, and on the metier practiced during the management season. The response may indeed affect any parameter of the exploitation model (Table 4, § 2.2).

In practice, policies and fishers' response are coded in Java^{TM}. The code describes the conditions under which the policy is applied and the way effort parameters are affected by policy implementation, as well as corresponding fishers' response. The model may consider any policy which can be structured as defined above. Several policies can be combined into a management scenario.

2.4. Fishers' behaviour

By definition, fishers' behaviour results in changing one or several effort parameters. Fishers' behaviour, either in response to a management scenario (as mentioned in § 2.3.), or in relation to economic conditions in the fishery, may alter fishing effort in different ways. Technological and tactical changes may occur due to the improvement of technologies. As in § 2.3, fishers' behaviour is coded in Java™. Any behaviour that can be written as a function or decision rule depending on model parameters or variables may be implemented.

For each policy, fishers' response to management is defined under the form of decision rules. For instance, fisher's response to TAC implementation is coded as follows : as soon as the TAC of a species is reached, the metiers for which the species is an important target reallocate effort to other metiers according to priorities depending on gear and strategy. Other metiers simply discard species catch altogether. In the case of MPA implementation, the metiers directly affected by the MPA are those whose metier zone intersects partially or totally with the management zone. When the intersection is partial, effort is reallocated to the rest of the metier zone; when the metier zone is enclosed in the management zone, fishers remain at port. These are only examples as other rules may be coded, e.g. switching to other metiers. There is no constraint on the kind of behaviour that can be coded, as long as it is consistent with the exploitation model. As a first example, the gravity model of Caddy (1975) has been coded in ISIS-Fish.

This model has been used in many instances to depict the allocation of fishing effort among fishing grounds or fishing activities (Walters et al. 1993; Seijo and Defeo 1994; Walters and Bonfil 1999). The model relies on the computation of probabilities of selecting an option (a fishing ground or a fishing activity) from the so-called "attractivity" of each choice (Caddy 1975), which is in general estimated from past outcomes of the fishery. (D)

In the long run, the gravity model yields a proxy for a short-term optimisation problem. Walters and Bonfil (1999) showed that this model converges to the Ideal Free Distribution of Fretwell and Lucas (1970). The gravity models already coded in ISIS-Fish pertain to the selection of metiers within a strategy. In a given strategy, attractivities per metier and per month may be computed in several ways.

As an example, the attractivity of a metier in a given strategy may depend on Landings Per Unit of Effort (LPUE) achieved in the previous year at the same month :

$$A(str,met,t) = LPUE\left(str,met,t\left(y-1\right)\right) = \frac{\sum_{pop} Landings\left(str,met,pop,t\left(y-1\right)\right)}{StdEffort\left(str,met,t\left(y-1\right)\right)} \quad (37)$$

where landings are given by Eq. (28). In this case, the attractivity of a metier is perceived through the tonnage of fish that can be landed for this particular metier.

Alternatively, attractivities may be computed from the Values Per Unit of Effort (VPUE) achieved in the previous year at the same month :

$$A(str,met,t) = VPUE\left(str,met,t\left(y-1\right)\right) = \frac{\sum_{pop} GrossValueLandings\left(str,met,pop,t\left(y-1\right)\right)}{StdEffort\left(str,met,t\left(y-1\right)\right)} \quad (38)$$

where landings are weighted by their price. Under this definition, the fisher allocates fishing effort based on the expected value of practicing a given metier. Note that the selection of a metier amounts to choosing a gear, a target species and a fishing location.

Two other options for computing attractivities rely on margins over variable costs:

(39) $$A(str, met, t) = \begin{cases} VesselMarginPerVessel(str, met, t(y-1)) \\ OwnerMarginPerVessel(str, met, t(y-1)) \end{cases},$$

where margins per vessel and metier are given by Eq. (33).

Alternatively, attractivities could be computed from other variables, or from values at different time steps in the past, including averages over time.

Once attractivities are computed, they are normalized to yield probabilities of selecting a given metier in a strategy. ISIS-Fish being a deterministic model, attractivities are then used as proportions of effort allocated to a given metier in a strategy, i.e. they are used to modify the current values of $PropMetStr(str, met, month)$ for the metiers and strategies concerned (Table 5 and Eq. (18)).

Previous equations were coded in Java™ , and are downloadable at http://isis-fish.labs.libre-entreprise.org/download or http://www.ifremer.fr/isis-fish.

Other kinds of behaviour may be coded from this language. For instance, empirical models of fishing effort allocation such as random utility models (Holland and Sutinen 1999; Hutton et al. 2004) may be implemented in ISIS-Fish.

Yet, it should be noted that computationally-intensive optimisation behaviours may not perform well due to the Java™ language and repeated accesses to the ISIS-Fish fishery database during the optimization. In this case, it is recommended that computations are deported to external applications, e.g. via .dll files.

2.5. Indicators for policy evaluation

To appraise the bioeconomic sustainability of the fishery under a range of a management scenarios, two kinds of indicators should be used: i) indicators of resource and catch status and dynamics, and ii) economic indicators. For policy evaluation, the former will allow to assess the sustainability of the resource, and the link between resource and catch in tonnage, while the latter will provide an assessment of the economic viability of the fishing units involved in the fishery.

2.5.1. Indicators of resource and catch status and dynamics

Most indicators rely on population abundance and resulting catch. In general, population dynamic models only provide a relative value of abundance, thus variables describing abundance are often interpreted in terms of variations over time. For the purpose of policy evaluation, we are generally interested in restoring depleted resources or improving catch, and in comparing several policies from this respect. Restoration of resources is detected from increases in abundance and biomass during the simulation. In certain cases like Leslie's models, population growth rates can be calculated (Pelletier and Magal 1996). It is generally not the case in the kind of models that can be developped under ISIS-Fish. Thus, indicators are constructed from trends in abundance and biomass under a given policy. Comparisons between policies are quantified through differences in population levels between policies and in the absence of policy.

These two aspects of policy evaluation are handled here by considering two indicators related to population biomass :

(40)
$$\begin{cases} BiomassRatio_{F/I}\left(pop\right)=\dfrac{Biomass_{final\ year}^{scenario}\left(pop,December\right)}{Biomass_{\text{second year}}^{\text{scenario}}\left(pop,December\right)} \\ BiomassRatio_{W/WO}\left(pop\right)=\dfrac{Biomass_{final\ year}^{\text{scenario}}\left(pop,December\right)}{Biomass_{\text{final}\,year}^{no\ policy}\left(pop,December\right)} \end{cases}$$

The first ratio is larger than 1 when population biomass increases during simulation, while the second one is larger than 1 when final biomass is larger under the policy considered than in the absence of policy. Biomass was considered rather than abundance, because it encompasses the restoration of both population abundance and population size structure. Similar ratios may be computed for abundance from simulation outcomes. We compared final biomass to biomass in year 2, rather than to year 1 to avoid a too large sensitivity of the ratio to initial conditions.
Similar indicators are considered for catch:

(41)
$$\begin{cases} CatchRatio_{F/I}\left(pop\right)=\dfrac{Catch_{final\ year}^{scenario}\left(pop,December\right)}{Catch_{\text{second year}}^{\text{scenario}}\left(pop,December\right)} \\ CatchRatio_{W/WO}\left(pop\right)=\dfrac{Catch_{final\ year}^{\text{scenario}}\left(pop,December\right)}{Catch_{\text{final}\,year}^{no\ policy}\left(pop,December\right)} \end{cases}$$

Again, we considered catch in tonnage rather than in numbers to account for both abundance and size structure restoration.

2.5.2. Economic indicators.

Several indicators of the economic viability of fleets may be calculated (see Martinet et al. (2007) for a discussion), such as gross margins, profit at full equity and net profit per strategy for each year. These are respectively calculated for each strategy as:

(42)
$$\begin{cases} GrossMargin\left(str,y\right)=\sum\limits_{months} OwnerMargin\left(str,t\right)-VesselCostsPerYear\left(sov\right) \\ FullEquityProfit\left(str,y\right)=GrossMargin\left(str,y\right)-CapitalDepreciationPerYear\left(sov\right) \\ NetProfit\left(str,y\right)=FullEquityProfit\left(str,y\right)-FinancialCosts\left(sov\right) \end{cases},$$

Profit at full equity corresponds to the return produced by the means used in the fishery by the strategy, while net profit accounts in addition for financial costs.
In the application section (§ 4), we will mostly rely on vessel margins to quantify the economic viability of the fishery. In order to compare policies and their ability to ensure an economically viable exploitation, ratios are calculated for gross value of landings and vessel margins, in the same way as in Eqs. (40) and (41).

(43) $$\begin{cases} VesselMarginRatio_{F/I} = \dfrac{OverallVesselMargin_{final\ year}^{scenario}\left(December\right)}{OverallVesselMargin_{second\ year}^{scenario}\left(December\right)} \\ VesselMarginRatio_{W/Wo} = \dfrac{OverallVesselMargin_{final\ year}^{scenario}\left(December\right)}{OverallVesselMargin_{final\ year}^{no\ policy}\left(December\right)} \end{cases},$$

(44) $$\begin{cases} StrategyGVLandingsRatio_{F/I}\left(str\right) = \dfrac{StrategyGVLandings_{final\ year}^{scenario}\left(str,December\right)}{StrategyGVLandings_{second\ year}^{scenario}\left(str,December\right)} \\ StrategyGVLandingsRatio_{W/Wo}\left(str\right) = \dfrac{StrategyGVLandings_{final\ year}^{scenario}\left(str,December\right)}{StrategyGVLandings_{final\ year}^{no\ policy}\left(str,December\right)} \end{cases},$$

where $OverallVesselMargin\left(t\right)$ is given by Eq. (36) and $OverallGVLandings\left(t\right)$ is the sum of $GrossValueLandings\left(str,met,pop,t\right)$ (Eq. (28)) over metiers and populations.

F/I ratios are thus used to assess the ability of a given policy to ensure population and fisheries sustainability, whereas W/Wo ratios are meant to compare the outcomes of a policy compared to a no policy scenario.

3. Software

3.1. User requirements.

The software was developped following a list of specifications related to user needs. Potential users of ISIS-Fish are advanced users like modellers, but also fisheries biologists, fisheries managers and other stakeholders. Modellers aim at using ISIS-Fish to assess and analyze consequences of management scenarios and their sensitivity to model assumptions and input data in order to derive general rules about fisheries dynamics and explore the interest of a range of policy options. Fisheries biologists may apply ISIS-Fish to the fishery they study and integrate corresponding knowledge in the software in order to obtain diagnostics and predictions about the consequences of management options. These can be used with fisheries managers and fishers to generate discussions about possible policy options and scenarios about fisheries dynamics. Such sessions might also be useful to convey messages about the importance of data quality and knowledge to ensure reliable fishery assessment.

A number of solutions have been experienced in versions 1.0 and 2.0, some of which had to be modified as their implementation with real applications was not fully satisfactory in terms of performance. We think it is important to share these experiences with other modellers, as the development of complex simulation tools is quite demanding in terms of human and financial resources.

3.2. Software development.

ISIS-Fish V3.0 has been developped following the class diagram described in Figure 1. The software was developped in a GNU-General Public License[1] (GPL) philosophy, i.e. the code is freely available and is made of free components. It is coded in Java™, and running version 3.0 of ISIS-Fish requires a Java Development Kit (JDK, versions 1.6 and later, freely downloadable at http://java.sun.com/javase/downloads/index.jsp) since the code is recompiled at the start of a

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[1] http://www.gnu.org/copyleft/gpl.html

simulation. Flexible parts of the code are also written in Java™. They include management measures, fisher's behaviour, and several functional relationships related to the population model (spawner-egg relationship, growth function and inverse growth function, natural mortality, migration coefficients, price) or to the exploitation model (selectivity equations, target factor). For each of these relationships, several functions are already coded and are available for selection in the user interface. Any newly coded function may be added to this library of existing functions, so that it is made available to all users. In previous versions of the software (Mahévas and Pelletier 2004; Pelletier and Mahévas 2005), flexible components were written in the ECMAScript language, but the Java^{TM} language is much quicker to run and facilitates syntax checking.

ISIS-Fish contains an embarked database containing all the information relative to a given fishery. To be able to re-use parameters or equations from other fisheries, databases can be easily loaded, modified and saved. Scripts coding for generic relationships, policies or fisher's behaviours may also be loaded.

An important feature of simulation tools is their ability to run quickly. In version 1.0, the architecture of the software was based on Entreprise Java Beans (EJB, Sun Microsystems). This was changed from version 2.0, as EJB required too much time and impeded simulation performances. In version 3.0, substantial effort was devoted to optimization of calculations, leading in particular to switch from matrix computations to optimized loops.

3.3. Running simulation experiments

Simulations can be run using the simulation interface. In general, a large number of simulations is required to address a given question, e.g. to evaluate a policy. First, sensitivity analyses have to be performed to account for uncertainties in input parameters and in some model assumptions. Second, it may be necessary to explore a variety of environmental or management scenarios.

Because ISIS-Fish focuses on the integration of available information and knowledge into a complex fishery model, much attention was given to running simulation experiments (Saltelli 2000; Cariboni et al. 2007). Simulation designs must involve combinations of policies, parameter values, and model assumptions to encompass a plausible range of "states of nature" for the fishery, and thereby ensure the reliability of model results through statistical analyses of numerous simulation outcomes. For this purpose, three functionalities were developped in the simulation interface: simulation queues, sensitivity analysis, and presimulation scripts.

The simulation queue enables the user to parameterize simulations one at a time and to add them in the queue for subsequent running. The batch of simulations can only involve changes in simulation input parameters, as the fishery parameters are stored in the database and cannot be changed through the simulation interface. Simulation input parameters are the number of years simulated, the populations and fishing strategies considered, initial stock sizes for each population, and the management measures considered with associated parameter values.

In the sensitivity analysis interface, the user may select a number of parameters for studying model sensitivity. Values to be considered for each parameter and combinations of those values for distinct parameters are specified in order to design a simulation experiment. The sensitivity of the model to alternative hypotheses on population dynamics (reproduction, zones…) may also be studied in the same way.

A presimulation script is a script run at the beginning of the simulation, before any model calculations. It is used in two instances : i) to change parameter values in the model without modifying the database; and ii) to speed up simulations in the case of some management measures. Hence, if the script contains the code for a management measure, simulating this measure does not require its specification in the main simulation interface. In the latter case, conditions of application of the measure are checked at each time step. Simulations based on presimulation scripts are thus much quicker. However, this is only possible for management measures with fixed parameters which are enforced throughout the simulation.

In the case of sensitivity analysis and presimulation scripts, parameter values are not modified in the database, but only during the simulation. This is convenient to ensure that the reference values for the parameters remain stored in the database. Furthermore, the script keeps track of changes in parameters, which facilitates simulation experiments.

Simulations generate masses of outcomes that may be either visualized in the results interface, or exported to be analysed using statistical softwares or spreadsheets. Population abundances, fishing effort, catch and discards and economic results may be exported. Additional exports tailored to particular needs may be specified using export functions. A package of scripts for exports is downloadable at http://isis-fish.labs.libre-entreprise.org/download. An example of simulation experiment in the case of a real fishery is presented in Drouineau et al. (2006).

4. Application

We illustrate the potential of ISIS-Fish to evaluate fisheries dynamics under management options in an economic setting with the example of a Northeast Atlantic mixed fishery. The simulations presented below do not provide a full analysis and diagnostic about the fishery and are not aimed at addressing all management issues regarding this fishery.

4.1. The Bay of Biscay Nephrops fishery.

The French *Nephrops norvegicus* fishery of the Northern Bay of Biscay is an important fishery on both economic and social levels, and at both local and national scales. There are about 230 French trawlers fishing for Nephrops in the Bay of Biscay (corresponding to ICES divisions VIIIa and b (Figure 2) with a total turnover of about 75 M€. In this area, Nephrops biomass is considered to be at a low level and a decline in catch rates is observed (ICES 2003a). Each year between September and November, Nephrops trawlers incidentally catch large amounts of juvenile hake in two major nursery areas of the Northern stock of hake. This latter stock has endured a high fishing pressure since the early 1990s, with an estimated fishing mortality close to F_{pa}, the fishing mortality corresponding the precautionary approach (ICES 2003b), and a currently very low level of Spawning Stock Biomass (SSB) (ICES 2003c). Yet, both Nephrops and hake stocks are presently regulated through TAC, together with minimum landing sizes, minimum mesh sizes and for Nephrops special exploitation permits. From 1970 to 1973, an MPA was established in the Bay of Biscay to protect juvenile hake but it was deemed inefficient, mainly due to inappropriate location. In 2001, hake “boxes” were implemented in the Bay of Biscay to protect juveniles through increased minimum mesh sizes (Commission of the European Communities 2001, 2002, 2004). Management measures aimed at protecting hake will thus affect Nephrops exploitation, and vice versa. In particular, an MPA aimed at protecting juvenile hake would impact fishers targetting Nephrops. In this paper, we focus on Nephrops population and on fishing activities impacting Nephrops.

We assume a sedentary age-structured population with a linear stock-recruitment relationship. The latter assumption stems from the lack of quantitative information about Nephrops reproduction and recruitment. Assuming a linear stock-recruitment relationship leads to a conventional Leslie model for the population (Caswell 1989) which is legitimate given the low population level. A discussion about the consequences upon fish population dynamics of alternative assumptions for stock-recruitment relationship may be found in Pelletier and Magal (1996). (E The population is spatially distributed over 9 ICES rectangles within ICES subdivisions VIIIa and VIIIb (Figure 2). All parameters required to define the Nephrops population dynamics are described in Tables 1, 2 and 3 of Drouineau et al. (2006). In this fishery, it is caught from age 1 with an age at first maturity of 2 years. Nephrops is caught by four sets of vessels, large and medium vessels from both Le Guilvinec (Figure 2) and Les Sables areas (Figure 2) with specific technical characteristics (Table 6). Within a given size class, vessels practice similar metiers and have similar fixed costs and metier costs (Table 7) irrespective of the port. Hence, between-port differences in fishing costs for a given vessel size class are due to differences in travelling distance to and from metier zones. All four sets of vessels are able to practice six metiers corresponding to possible combinations of a gear (simple trawl or twin trawl) and a target species, the latter determining distinct metier zones (Table 8). All metiers catch Nephrops. Target factors for Nephrops are estimated as the metier effect in linear models of Nephrops catch rates (Drouineau et al. 2006, Table 8). The selectivity function for single and twin trawl is given by the generic formula:

$$s(L) = \frac{\exp[\frac{1}{MS*SF*SelR}*2*\ln(3)*(L-MS*SelR)]}{1+\exp[\frac{1}{MS*SF*SelR}*2*\ln(3)*(L-MS*SelR)]},$$

where *L* is fish length, *MS* is the mesh size (here set at 70mm), and *SF*=0.5 and *SelR*=0.43 are the two selectivity parameters for Nephrops (ICES 1992). The standardisation factor of single trawl (resp. twin trawl) is set to 1 (resp. 1.39), i.e. twin trawl is assumed to be 1.39 times more efficient than single trawl (A. Biseau comm. pers., 2006). Twelve strategies are considered, combining metiers practiced and the sets of vessels defined above (Table 9). For each strategy, the number of vessels and the monthly proportions of vessels practicing a given metier were computed from fisheries logbook data. As these data do not distinguish between twin trawl and single trawl, monthly proportions for these gears are identical for a given target species (Table 9). In order to account for other species contributing to the metiers' revenue while avoiding explicit modelling of these species, positive values were assigned to the parameter *OtherSpeciesGrossValue(str,met)* (Table 5, Eq. (31)). These values decrease as the overall effort of the fishery increases and they are specific to each strategy:

$$OtherSpeciesGrossValue(str,met) = \begin{cases} 10^6 - 10*StdEffortFishery & \text{for Benthic strategies} \\ 8.10^4 - 50*StdEffortFishery & \text{for Hake strategies} \\ 5.10^4 - 100*StdEffortFishery & \text{for Nephrops strategies} \end{cases},$$

where i) $StdEffortFishery = \sum_{str}\sum_{met} StdEffort(str,met)$; ii) Benthic strategies include strategies BMedGV, BMedLS, BLarGV, BLarLS; iii) Hake strategies include HMedGV, HMedLS, HLarGV, HLarLS; and iv) Nephrops strategies include NMedGV, NMedLS, NLarGV, NLarLS (Table 9).

We evaluated a range of management scenarios over a simulation period of ten years, assuming that parameter values remain valid over that time horizon. Scenarios considered include no policy, implementation of an MPA in part of the Nephrops distribution area corresponding to hake nursery areas (Figure 2), prohibition of twin trawl, and TAC (Table 10). Each management scenario was assessed under two assumptions about fleet dynamics : i) effort allocation is static from year to year but for fisher's response to management (Table 10); and ii) effort dynamics is driven by both fisher's response to management and economic conditions through a gravity model (§ 2.4). (F) For each strategy and metier of this strategy, we used the gravity model based on Values per Unit Effort (Eq. 38) modified to account for other species gross value:

$$A(str,met,t) = \frac{\sum_{pop} GrossValueLandings(str,met,pop,t(y-1)) + OtherSpeciesGrossValue(str,met)}{StdEffort(str,met,t(y-1))}$$

The initial distribution of Nephrops abundance per population zone is (0, 5.977.10^4, 4977, 2944, 1177, 461, 195, 95, 52, 58) thousands of individuals.

4.2. Results

With regard to resource sustainability, Nephrops appears overexploited under the current situation ("No Policy"). Hence, Nephrops biomass declines and then stabilizes after 5 years at a level of 30% of the initial biomass (Figure 3a) when fishing effort allocation is static. In the case of dynamic effort allocation, biomasses at a given date and for a given scenario are consistently lower than under static effort allocation.

Out of the three policy options tested, the MPA and twin trawl ban appear to restore Nephrops, while the TAC tested (which is quite restrictive, Table 10) leads to lower biomasses than the "No Policy" option. A smaller TAC (400 t) was also tested; results (not reported here) indicate a slightly higher biomass but are in essence similar. The MPA restores biomass under both dynamic and static effort allocation, whereas the twin trawl ban stabilizes the population under dynamic effort allocation and restores it in the static case with an increase in biomass from year 7 of the simulations.

Most consequences of policies may be explained by fisher's response to management. In the case of a TAC, fishers for which Nephrops is not the main target (four metiers out of six, Table 8) continue fishing in the same way once the TAC is reached, and discard Nephrops catch. Consequently Nephrops landings are zero but catch of these fishers remain unchanged as showed by the second peak of catch during the first simulation years, Figures 3c-d). This effect is magnified by the fact that after the TAC is reached, Nephrops metiers reallocate effort to the above mentioned metiers. Overall, this results in the collapse of the Nephrops stock. In the case of twin trawl prohibition, all fishers using twin trawl switch to single trawl (Figures 3c-d). Because simple trawl is less efficient than twin trawl, Nephrops is less impacted by fishing and thus population sustainability is ensured. The establishment of the MPA leads to a more dramatic reduction in fishing mortality. The closed area encompasses 2/9 of Nephrops distribution area and its implementation results in a reduction of 1/3 of the fishing zone impacting Nephrops, since the concerned fishers partly reallocated effort outside the Nephrops distribution area (Table 10). In the unfished area, spawning biomass substantially increases and ensures population sustainability. However the MPA does not contribute to an overall increase in population abundance over its entire distribution area, because of the assumption of restricted larval dispersion that prevents spillover outside the MPA. Consequently catch does not increase as much as with the twin trawl ban. Alternative hypotheses about larval dispersion such as e.g. a larval pool might have resulted in different results, but there was no scientific evidence for such hypotheses. Yet, these should be considered in sensitivity analyses.

We also assessed the impact of a temporary opening of the MPA in November and December, but it dissipated the benefit of the MPA within the year (results not reported here).

In terms of catch, it should be noted that the twin trawl ban yields the highest catch over the entire period. Yet, under a dynamic effort allocation, seasonal patterns vary over years and thus catch is less even.

In terms of overall economic return for the fishery, F/I ratios of vessel margins indicate that the MPA, TAC and "No Policy" scenarios result in a decreased economic return, irrespective of the assumption on the effort allocation (Figures 4a-b). The current situation ("No Policy") appears not sustainable neither for the resource nor for the fleet. The TAC is clearly the worse option, even including revenues from other species, while the MPA and "No Policy" option results in similar returns. In contrast, the twin trawl exclusion improves vessel margins over a 10 years time horizon. Consistently with these results, W/Wo ratios of vessels margins show that the twin trawl is the only scenario that improves both stock status and economic return for the fleet (Figures 4c-d). The MPA option improves stock status but not the economic return, due to assumptions about larval dispersion (see above). Under the twin trawl exclusion, the increase in economic return after 10 years is ca. 10% (resp. 7%) in the case of a static (resp. dynamic) allocation. Compared to the "No Policy" scenario, the increase in economic return is ca. 15% (resp. 18%) in the case of a static (resp. dynamic) allocation after 10 years.

Whether for biomass and catch trajectories or for vessel margin ratios, results are not qualitatively affected by the assumption about effort allocation (Figures 4a and c versus 4b and d).

It is then interesting to compare the consequences of policy options at the strategy level, e.g. through gross values of landings per strategy (Figure 5, in the case of a static allocation of fishing effort). Gross values of landings include both Nephrops and other species. Strategies are not similarly affected by scenarios due to differences in costs according to vessel size, gear operated and fishing locations. Whatever the policy option, most strategies that do not specifically target Nephrops (Benthic and Hake strategies) maintained or increased gross revenues over the simulation period whatever the policy (Figure 5a). In contrast, the revenues of the four strategies targeting Nephrops strongly decreased over the simulation period. The MPA and twin trawl exclusion benefitted most to the strategies that do not target Nephrops to the exception of the strategy HMedGV. The W/Wo ratios confirm that the twin trawl is the best option for the fleet among the one tested, as for each strategy the gross values of landings at the end of the simulation period are larger than with any of the three other options tested.

Landing gross values for strategies targetting Nephrops (last four strategies in Figure 5) are more sensitive to management scenarios than the other strategies. F/I ratios of gross value of landings are the lowest, reflecting the lack of ability of these scenarios to ensure economic sustainability of Nephrops exploitation (Figure 5a). These results are partly explained by the spatial location of fishing activities. For instance, the fishing grounds of the medium vessels from Les Sables overlap less with the Nephrops distribution area than the fishing grounds of the medium vessels from Le Guilvinec. Consequently, a management measure reducing fishing pressure within the Nephrops distribution area will have less impact on the former vessels. Hence, for a given vessel size and fishing activity, vessels from Le Guilvinec always exhibit a lower ratio of landing gross values than vessels from les Sables (Figure 5a). Between strategies differences in W/Wo ratio are much large under MPA management than under the twin trawl ban.

This illustration thus shows the need for appraising economic consequences at the strategy levels. The results obtained for each policy considered indicate that it would interesting to investigate combinations of management scenarios, for instance a MPA together with a gear restriction.

Note that regarding biological assumptions, it would be interesting to explore the potential impact of a larval dispersion over the whole Nephrops distribution area, and of other stock-recruitment relationships.

5. Discussion-Perspectives

5.1. An original bioeconomic model for policy screening.

In this paper, we presented ISIS-Fish, a bioeconomic model aimed at investigating a variety of management policies. This model includes several novel features compared to existing models. First, in many bioeconomic fisheries models, the biological submodel is simplified. It generally relies on a logistic growth, e.g. in Sanchirico and Wilen (2001a and b). They studied the impact of MPA (only permanent no-take zones) creation within a three-patch system under different assumptions about biological connectivities between patches (closed populations, adjacent populations linked, all populations linked). The model did not apply to an actual fishery. Holland (2000)’s model includes more detail about resource dynamics by considering age structure, seasonal oriented migrations, permanent dispersion of adult fish and a larval pool. The model was applied to an existing mixed fishery, but it is not intended to be generic.

Second, many bioeconomic models do not consider mixed fisheries, i.e. multifleet multispecies fisheries, which are nevertheless the majority of fisheries. In such fisheries, fishers are confronted to choices between several possible fishing activities (metiers) corresponding to distinct gears, fishing grounds, and target species. Their choice depends on economic conditions and management constraints, therefore simple models where exploitation is only described through a single parameter such as fishing effort or fishing mortality are not suitable for investigating the consequences of management options. In Holland (2000)’s model the economic relationships are modelled through short-term allocation of fishing effort parameterized from empirical modelling of field data (Holland and Sutinen 1999). In ISIS-Fish, the spatially-explicit model enables proper account of seasonal effort dynamics in relation to resource dynamics, and this dynamics may be altered by other factors, such as economic conditions, policies, or strategy behaviour. Fisher's behaviour is modelled in a flexible way, so that empirically estimated decision rules such as those in Holland and Sutinen (1999) and Hutton et al. (2004) can be easily considered. The results presented hereabove show the interest of analysing policy consequences for each strategy involved in the fishery, as they may be affected in different ways.

A key feature of ISIS-Fish is the attention paid to fisher's response to management. It is widely acknowledged that the impact of any management measure largely depends upon the way fishing effort is reallocated after its implementation. In the case of MPA, many models assume that effort uniformly redistributes over the remaining fisheries area. Another example of fishers' response to management is provided by discarding or highgrading behaviours that may result from TAC regulations (Ulrich et al. 2002). In bioeconomic models, fisher's response is generally made endogeneous under the classical assumption of optimal behaviour of economic agents, resulting in models that are difficult to parameterize from real data. For instance, game theory may be used to model fisher's response (Beattie et al. 2002; Sumaila 2002) : fleets may either cooperate, i.e. maximize the joint benefit to the fishery, or maximize their own benefit. Besides, many models are unsuitable to investigate fisher's response either because effort distribution is static, or because fishing effort dynamics is not directly affected by policies. Beyond theoretical behaviour models, it is thus relevant to consider responses that can be modelled from actual observations, e.g from ad hoc fishers' interviews. However, empirical studies designed in this purpose are still scarce (Rijnsdorp et al. 2001). In ISIS-Fish, fisher's response to policy is part of fisher's behaviour, it is thus modelled in the same way, e.g. on the basis of empirical studies.

Regarding cost modelling, Sanchirico and Wilen (2001b)'s model includes overall costs (opportunity cost tied to vessel capital and ex-vessel price) and patch-specific costs per unit effort (i.e. variable costs). The model was adapted by Sanchirico and Wilen (2001a) to depict a limited-entry fishery managed through vessel licenses. The rent then comprises as well the opportunity cost tied to license price. In the ECOSEED model of Beattie et al. (2002), each fishing ground is assigned an economic value that encompasses revenues per fleet and per biomass pool and existence values of species pools, as well as fixed costs and operating costs. In contrast, in our model costs are not attached to fishing grounds, but relate to different components of fishing effort : vessels, strategies, metiers. In addition, the spatial model enables one to distinguish traveling costs from fishing costs. This is required if one wants to explore consequences of changes in fishing activities resulting from policy implementation. Such changes may operate at the trip scale (e.g. changing metiers by switching gear or fishing ground), at the season scale (e.g. changing metiers practised in strategy), or at the year scale (e.g. changing strategies). The costs involved by each change are distinct, and unlike existing models, ISIS-Fish enables one to assess quantitative consequences of such changes, provided that these costs can be estimated for input in the model.

The variety of exploitation costs considered may be estimated from interviews or accounting data when available. It may happen that information is only partially available, for instance for some groups of vessels or some ports. In this case, the model can be simplified or sensitivity analysis may be run to check whether or not the missing parameter is critical.

With respect to the scenarios investigated, it should be noted that to the exception of Beattie et al. (2002) who considered a trawl-exclusion scenario, published bioeconomic models only addressed no-take zones, and not MPAs in the form of spatial restrictions of targeted fishing activities. The establishment of an MPA is generally modelled as a fraction of the region closed or a constraint on effort allocation and MPA are rarely compared with other management measures. In addition, few models allow investigating the performance of combined management policies. However, such investigations are necessary because the ability of MPA to ensure resource conservation and reduce overexploitation is much improved when additional management measures are simultaneously implemented.

Although it depicts a simplified case (models involving several species are currently under development), the application illustrates the kind of results obtained from the model. It shows that in the case of overexploitation, the MPA scenario may be a better option than TAC or twin trawl prohibition with respect to resource sustainability, but that the twin trawl prohibition provides better overall economic margins. However, economic results differ among strategies. Although the economic rent at fisheries scale is relevant for assessing the general interest of a policy, comparing policy implications across fleets brings indispensable insight to assess the equity of management measures. From this standpoint, it is necessary to understand fisheries dynamics and identify winners and losers, in particular in complex fisheries. ISIS-Fish is definitely designed for this kind of objective, However, it may be used for conducting more theoretical exercises.

Note that, as is the case with most existing bioeconomic models, the present version of ISIS-Fish does not describe entry and exit of vessels, as it is focused on short-term allocation of fishing effort and its consequences on the performance of management options. However, it could still be achieved through appropriate scripts describing the relationships between investment and economic results for each strategy and set of vessels.

5.2. Parameterization of a complex model: data requirements and uncertainties.

As discussed in § 5.1, ISIS-Fish makes it possible to consider simple or detailed models either for population dynamics, exploitation dynamics, policies or fisher's response. The level of detail of the model will differ among the applications, depending on the questions addressed and on the level of information available for parameterization. It is thus indispensable to devise simulation experiments that enable accounting for the consequences of uncertainties in input parameters and assumptions on model outcomes. An important aim of ISIS-Fish is to serve as a decision-support tool for fisheries management, thus particular attention was given to the parameterization issue in software development.

In so far as possible, selecting model assumptions and estimating model parameters can be achieved from the information usually available in fisheries and marine ecology, from both expert knowledge and data analyses. In such complex spatial models, developing a built-in estimation procedure is problematic. Thus, main parameters in ISIS-Fish can be estimated by statistical analyses independently of the model and in a consistent way with respect to model equations. Although not fully rigorous from a statistical standpoint, this approach is pragmatic. For the population model, most parameters have a real meaning and can be estimated from independent data sets, e.g. the growth function or migration coefficients. Time-series of abundance indices, for instance obtained from stock assessments, together with recruitment indices enable to appraise stock-recruit relationships (Kraus et al. (under press)). Likewise, population zones may be delineated from multivariate analyses (see e.g. Pelletier and Magal 1996) as well as fishing grounds (Pelletier and Ferraris 2000). (G) Regarding exploitation-related parameters, they can be estimated from the kind of information available in documented fisheries (e.g. commercial logbook data, fishers interviews, observer data, etc.). Note also that the spatial resolution of ISIS-Fish may be adapted to the level of knowledge and data availability to facilitate integration of available information about the fishery. Also, scripts have been written to facilitate model calibration by numerical algorithms (http://isis-fish.labs.libre-entreprise.org/download).

As for remaining uncertainties, facilities for running simulation experiments and sensitivity analyses were included (§ 3.3). These are indispensable, as numerous simulations are required for policy-screening. Methods for designing simulation experiments for sensitivity analysis have e.g. been proposed by Saltelli et al. (2000).

We are currently working on the design of additional routines and scripts to facilitate i) the estimation of input parameters, and ii) the graphical and statistical analysis of simulation outcomes.

5.3. A generic tool for decision-support

Due to its complexity and numerous features, developing ISIS-Fish was demanding in terms of both effort and time. For this reason, this kind of tool has to be applicable to as many fisheries as possible. Therefore, the software should be easy to use. The first point lies in its ability to incorporate improved knowledge about the fishery and changes in some model assumptions. Secondly, model components may be reused from existing applications. Thirdly, the software was developped under a GNU General Public License and is freely available (http://isis-fish.labs.libre-entreprise.org/). Substantial effort was devoted to software documentation through user manual and contextual help. Mailing lists for users and developers were organized to share experiences with the software and they greatly contribute to its improvement, in both user interfaces, model structure and simulation performance.

In the field of marine resource modelling, we are aware of no other software with such specifications as ISIS-Fish. Yet, to date, developing an application of ISIS-Fish requires modelling skills or a close interaction with a modeler. An objective of the project is to further facilitate the use of the software through i) a documentation that is detailed and easily available, and ii) an organization that enhances sharing of experiences among users.

From our experience, this kind of software represents an interesting tool for collaborative work between modelers, fisheries scientists and ecologists. It provides, in addition, a support for communication with marine resource managers.

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Appendix. Modelling of biological processes

Change of class

For age-structured populations, fish change ages at the beginning of each year. For length-structured populations, fish may change classes at the beginning of each month, as a function of length class and growth. In stage-structured populations, fish may change stages at the beginning of each month as a function of growth and maturity ogive. Possible seasonal variations in growth are handled through a proportion of fish changing classes that depends on population season. For each population season, a block diagonal matrix $\mathbf{CC}_{\mathbf{season}}$ of dimension $n \times NbClass$ was defined:

$$\mathrm{CC}_{\mathbf{season}} = \begin{bmatrix} CC_{Z1} & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & CC_{Zi} & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & CC_{Zn} \end{bmatrix}, \tag{A.1}$$

where each block $\mathbf{CC_{Zi}}$ is a square matrix of dimension *NbClass* and of element cc_{ij} the proportion of class *j* growing to class *i* at the beginning of each month of the season in zone **Zi**. Note that cc_{ij} is zero for i < j, $\sum_{j=1}^{\mathrm{NbClass}} cc_{ij} = 1,$ and $cc_{NbClass,NbClass} = 1$ in case of a plus group. Class changes can be made easily dependent on population zones given the matrix formulation.

Migrations

Migrations include migrations between population zones, emigration outside of the fishery area, and immigration into the fishery area. Migration and emigration are modelled by age-specific migration rates, whereas immigration is described by an abundance vector. At the beginning of each population season, migration processes determine the spatial distribution of abundance before other processes take place. Migration and emigration rates are arranged into a matrix $D_{\mathbf{season}}^{\mathbf{mig}}$, a block diagonal matrix :

$$D_{\mathbf{season}}^{\mathbf{mig}} = \begin{bmatrix} D_{11} & \cdots & D_{i1} & \cdots & D_{n1} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ D_{1\mathrm{j}} & \cdots & D_{ij} & \cdots & D_{nj} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ D_{1\mathrm{n}} & \cdots & D_{in} & \cdots & D_{nn} \end{bmatrix}, \tag{A.2}$$

where $\boldsymbol{D_{ij}}$ is a diagonal matrix of dimension *NbClass* of c^{th} diagonal element :

$$d_{ij}(c) = \begin{cases} m_{ij}(c) \ \text{ if } \ i \neq j \\ 1 - \sum_{i \neq j} m_{ij}(c) - e_i(c) \ \text{ if } \ i = j \end{cases}, \tag{A.3}$$

where $e_i(c)$ is the emigration coefficient from class c outside population zone i, and $m_{ij}(c)$ is the migration rate of class c from population zone j to population zone i at the beginning of the season. Note that $d_{ii}(c)$ corresponds to the proportion of fish of class c staying in zone i.

Possible immigration is modelled through $N_{\mathbf{season}}^{\mathbf{immig}}$, a vector structured like N(t) (Eq. (1)), denoting the number of fish per class immigrating into the fishery area at the beginning of the season.

Reproduction and recruitment

For many fish populations, reproduction and recruitment take place in distinct zones and at different times of the year. Several reproduction zones (spawning areas) and several recruitment zones per population may be specified for each population. Several recruitment areas (nurseries) can be associated to a given spawning area, in which case births are uniformly distributed among recruitment zones and conversely, several spawning areas may contribute to a given recruitment area. The contribution may be quantified, allowing to consider metapopulation structures and a variety of larval dispersion and settlement schemes.

Reproduction occurs at each month of the reproduction season delimited by starting and ending months, $t_{repro}^{\inf}$ and $t_{repro}^{\sup}$. Reproduction outcome may depend on the parental stock, e.g. it may be chosen among known relationships like Ricker, Beverton-Holt models, or alternatively any another relationship may be written. The number of births at time t in reproduction zone z is :

$$N_{birth}(t,z) = p_{repro}(t)\, f_{sr}\left(N_{sp}(t,z)\right), \tag{A.4}$$

where f_{sr} represents the relationship between spawner abundance and reproduction outcome, which may depend on additional parameters, and $N_{sp}(t,z)$ is the number of mature animals in z at t. $p_{repro}(t)$ is the proportion of mature individuals ready for reproduction at time t, and accounts for the temporal spread of reproduction over the reproduction season.

For a monthly cohort of births, recruitment duration is determined by the minimum time Δ_{rec} and the maximum time required by a newborn to recruit denoted $\Delta_{\mathrm{rec}} + \tau_{rec}$. The corresponding time interval may be seen as resulting from individual variation in development. Recruitment season is hence determined by both recruitment duration for a cohort, and by the length of the reproduction season, i.e. it starts at month $t_{repro}^{\inf} + \Delta_{rec}$, and finishes at month $t_{repro}^{\sup} + \Delta_{rec} + \tau_{rec}$.

Under these assumptions, the number of fish recruiting in recruitment zone z_{rec} at a given month of the recruitment season is :

$$N_{rec}(t, z_{rec}) = \frac{1}{n_{zrec}} \sum_{i=1}^{\tau_{rec}} p_{rec}(i)\, N_{birth}\left(t - \Delta - i - t_{repro}^{\inf} + 1, z_{repro}\right) \exp\left(-M_{birth}(\Delta + i - 1)\right), \tag{A.5}$$

where $p_{rec}(i)$ denotes the proportion of a cohort that recruits at the i^{th} time (recall that a cohort recruits during τ_{rec} months); thereby accounting for the temporal distribution of recruitment over recruitment season. n_{zrec} is the number of recruitment zones associated to z_{repro}, and M_{birth} is the natural mortality rate of new borns (in months^{-1}) until they recruit. $N_{rec}(t, z_{rec})$ is arranged into a recruitment vector **R(t).**

Tables

Table 1. Attributes of model objects in Figure 1. Attributes are defined in Tables 2-4.

Model Object	**Attributes**
Fishery Area	Name, MinLat, MaxLat, MinLon, MaxLon, SpatialResolutionLat, SpatialResolutionLon
Cell	Name, Latitude, Longitude,
Zone	Name
Port	Name
Season	StartingMonth, EndingMonth
Species	Name, ScientificName, PopulationStructure
Population	Name, AgeAtMaturity, PlusGroup,GrowthModel, InverseGrowthModel, NaturalMortalityOfNewBorns, NumberOfMonthsBetweenBirthAndRecruitment, DistributionOfRecruitment, MatchBetweenSpawningAndRecruitmentAreas, SpawnerEggRelationship
Population Class	Identifier, MeanWeight, FecundityCoefficient, NaturalMortality,PricePerKg
PopulationSeasonInfo	ChangeOfClass, ChangeOfAgeMonth, ChangeOfClassMatrix, Reproduction DistributionOfSpawning
Migration	MigrationCoefficient
Emigration	EmigrationCoefficient
Immigration	ImmigrationNumber
Gear	Name, EffortUnit, Standardisationfactor, TechnicalParameter, RangeOfValues
Selectivity	Equation
Metier	Name
MetierSeasonInfo	
TargetSpecies	TargetFactor, Maincatch
Catchability	CatchabilityCoefficient
TripType	Name, TripDuration
VesselType	Length, Speed, MaxTripDuration, ActivityRange, MinimumCrewSize, UnitFuelCostPerHour, Possible TripTypes
SetOfVessels	Name, NumberOfVessels, VesselCostsPerYear
MetierEffortDescription	NumberOperationsPerDay, FishingOperationDuration, GearNumberPerOperation, CrewSize, UnitCostOfFishing, CrewShareRate, RepairAndMaintenanceGearCostsPerDay, LandingCostsRate, OtherRunningCosts,
Strategy	PropSetOfVessels
StrategyMonthInfo	MinInactivityDays, PropMetStrMonth

Table 2. Fishery area and associated objects in the fishery database with corresponding parameters. The tab column indicates where the attributes of each object are accessible in the input interface.

Database object	**Tab in the input interface**	**Parameter**	**Parameter definition**	**Type**
Fishery area	Fishery area / Definition	Fishery area name	The name of the fishery area. The area is a rectangle with a regular grid of cells	character string
		Fishery area boundaries: Min. Lat., Max. Lat, Min. Lon., Max. Lon.	The boundaries are defined by minimum and maximum longitudes and latitudes	signed real
		Spatial resolution:	Spatial extent of each cell in latitude and longitude	
		Lat.		signed real
		Lon.		signed real
Cell	Fishery area / Cells	Name	Name of the grid cell	character string
		Latitude	Latitude of bottom left corner of the grid cell	signed real
		Longitude	Longitude of bottom left corner of the grid cell	signed real
		Land	True if the cell is located on land	boolean
Zones	Fishery area / Zones	Name	Name of a subarea of the fishery area corresponding to the spatial distribution of a population class or of a fishing activity, and to management areas[1]	character string
		Cells composing the zone	List of grid cells composing the subarea	subset of Cells
Ports	Fishery area / Ports	Name	Port name	character string
		Cell	Grid cell corresponding to port location	one Cell

[1] Zones are defined independently of each other.

Table 3. Objects associated to the population model as defined in the fishery database and corresponding parameters. The tab column indicates where the attributes of each object are accessible in the input interface.

Database object	**Tab in the interface**	**Parameter**	**Parameter definition**	**Type**
Species	Species	Name	Common name	character string
		Scientific name	Scientific name	character string
		Population structure	Indicates whether population dynamics is stage- or age-structured	boolean
Population	Species/ Population / Biological parameters / Population parameters	Name	Population name	character string
		Number of classes	If stage-structured population, number of stages; if age-structured population, number of age classes	integer
		Age at maturity	Age at which 50% of the individuals are mature	integer
		Plus group	If the last group is defined as a plus group	boolean
		Growth curve	Growth curve of the population with corresponding parameters	equation
		Inverse growth curve	Inverse of growth curve with corresponding parameters	equation
Class	Species/ Population / Biological parameters / Class-specific parameters	Mean weight	Mean weight of the class (in kg)	real
		Price	Price (in euros per kg) of the class	equation
		Fecundity coefficient	Number of eggs per kg of female of the class	real
		Natural mortality	Natural mortality coefficient for the class in year^{-1}	integer
		Age	If the population is stage-structured, mean age in the stage (relevant for stage-structured populations)	real
		Length	If the population is age-structured, mean length in the age class (relevant for age-structured populations)	
Population	Species/ Population / Zones	Population areas	Zones where the population is found during the year	set of Zones
		Spawning areas	Zones where the population spawns	set of Zones
		Recruitment areas	Zones where the population recruits	set of Zones
		Match between spawning and recruitment areas	Defines the proportion of eggs from a given spawning area that recruit in a given recruitment area	matrix of proportions
Population Season	Species/ Population / Seasons	Season	***Set of consecutive months at the beginning of which change of class, migration or reproduction may occur***	set of months
		Change of class	***Indicates whether change of class takes place during this season***	boolean
		Change of age month	***If age-structured population, month at which animals change age classes***	month
		Change of class matrix	***If stage-structured population, proportions of individuals changing classes at each month of the season (and possibly per area)***	matrix of proportions
		Reproduction	***Indicates whether reproduction takes place during this season***	boolean
		Distribution of spawning	Relative intensity of reproduction per month of the spawning season (i.e. the proportion of matures reproducing per month of that season)	vector of proportions

Table 3. (end).

Database Object	**Tab in the input interface**	**Parameter**	**Parameter definition**	**Type**
Catchability	Species / Population / Catchability	Catchability coefficient	For each class and each season, a catchability coefficient defined as the probability of a fish of the class present in the population area during the season, to be caught by a unit of standardized effort from a non selective gear.	matrix of coefficients (dimension number of classes X number of season)
Population	Species / Population / Reproduction-Recruitment	Spawner-egg relationship	An equation giving the number of eggs spawned as a function of spawner abundance and other parameters, possibly including fecundity coefficient	equation
		Natural mortality of new borns	Natural mortality endured by new borns between birth and recruitment (in year^{-1})	real
		Number of months between birth and recruitment	Minimum time required by a new born fish to reach recruitment. It determines the beginning of recruitment season from the reproduction season	integer
		Distribution of recruitment	Probability that a new born ready to recruit effectively recruits for each corresponding month. It reflects individual variability in egg and larval development	vector of proportions
Population Season	Species / Population / Migrations	Class migrating	Class for which the migration is being defined	class identifier
		Season	Season at the beginning of which the class is migrating	set of months
		Migration coefficient(*)	Proportion of the class migrating at the beginning of the season	real between 0 and 1
		Immigration number	Numbers of fish of the class immigrating at the beginning of the season	real
		Emigration coefficient(*)	Proportion of the class emigrating outside of the fishery area at the beginning of the season	real between 0 and 1
		Departure area	Departure zone for the migration being specified	Zone
		Arrival area	Arrival zone for the migration being specified	Zone

(*) These proportions are equivalent to class-specific transfer rates

Table 4. Objects associated to the exploitation model as defined in the fishery database and corresponding parameters. The tab indicates where the attributes of each object are accessible in the input interface. Parameters are denoted as in the input interface.

Object	**Tab in the interface**	**Parameter**	**Parameter definition**	**Type**
Gear	Characteristics	Name	Gear name	Character string
		Effort unit	Unit in which the effort of the gear is measured	Character string
		Standardisation factor	Factor to standardize fishing effort among gears	Positive real
		Technical parameter	Parameter possibly affected by technical management measures	Character string
		Range of values	Set of possible values of the technical parameter :	
			-type of parameter value	-String, integer or real
			-range of values	-List of discrete values or interval of values
	Selectivity	Selectivity equation	Selectivity equation for each species that can be caught by the gear	Equation
Metier	Characteristics	Name	Metier name	Character string
		Gear	Gear used by the metier	Gear
		Gear parameter value	Value of the technical parameter of the gear as used by the metier	Parameter value for the metier
	Seasons/Zones	Season	Suite of months during which the metier is practised	Set of consecutive months
		Zones	For each season, list of zones where the metier is practised	Zones
	Catchable population	Season	Metier season for which the catchable population is being specified	Season
		TargetFactor	Coefficient that quantifies the strength with which a metier targets the population. It encompasses fishing power, fine tuning of gears,..	Positive real
		Main catch	True if the population is a major target for the metier.	Boolean
Trip Types	Trip Types	Name	Name of the trip type	Character string
		Trip duration	Number of days at sea per trip of this type (including travel time)	Integer
		MinTimeBetweenTrips	Minimum number of days between two trips for a trip of this type	Integer
Vessel Types	Vessel Types	Name	Name of the vessel type	Character string
		Speed	Mean speed of a vessel of this type in km.h^{-1}	Positive real
		MaximumTripDuration	Maximum number of days at sea for a vessel of this type	Integer
		ActivityRange	Maximum distance from the port (in km) for a vessel of this type	Positive real
		MinimumCrewSize	Minimum crew onboard to operate a vessel of this type	Integer
		Length	Mean length (in m) for a vessel of this type	Positive real
		UnitFuelCostTravel	Fuel cost per hour of travel time (in euros)	Positive real
		Possible TripTypes	Trip types possibly operated by a vessel of this type	TripType

Table 4 (end).

Database Object	**Tab in the input interface**	**Parameter**	**Parameter definition**	**Type**
Set Of Vessels	Characteristics	Name	Name of the SetOfVessels	Character string
		Port	Port from which vessels of the SetOfVessels operate	Port
		VesselType	Vessel type for this SetOfVessels	VesselType
		NumberOfVessels	Number of vessels in the SetOfVessels	Integer
		VesselCostsPerYear	Fixed costs (in euros)	Positive real
	MetierEffortDescription	Metier	A metier possibly practised by the SetOfVessels	Metier
		NumberOperationsPerDay	Number of fishing operations per day for this metier	Positive real
		FishingOperationDuration	Duration of a fishing operation (in hours) for this metier	Positive real
		GearsNumberPerOperation	Number of gears used per fishing operation for this metier	Positive real
		CrewSize	Number of crew onboard to operate this metier	Integer
		UnitCostOfFishing	Fuel, oil, and ice costs per fishing operation (in euros) for a vessel of this SetOfVessels practicing this metier	Positive real
		FixedCrewSalary	Fixed part of the salary for the whole crew of a vessel of this SetOfVessels practicing this metier (in euros per month)	Positive real
		CrewFoodCosts	Food costs for the crew of a vessel of this SetOfVessels practicing this metier (in euros per day)	Positive real
		CrewShareRate	Crew share rate for a vessel of this SetOfVessels practicing this metier	Positive real
		GearMaintenanceCostsPerDay	Repair and maintenance gear costs per fishing day for a vessel practicing this metier (in euros per day)	Positive real
		LandingCostRate	Landing cost rate linked to this metier and to the port of the strategy	Real between 0 and 1
		OtherRunningCosts	Other running costs for a vessel of this SetOfVessels practicing this metier (in euros per hour)	Positive real
		OtherSpeciesGrossValue	Gross value from species not explicitly modelled	Positive real
Strategies	Characteristics	SetOfVessels	SetOfVessels to which the vessels of the strategy belong	SetOfVessels
		PropSetOfVessels	Proportion of the number of vessels of the SetOfVessels that pertain to the strategy	Real between 0 and 1
	ActivityPerMonth	TripType	TripType practised during the month by the vessels of the strategy	Positive real
		MinInactivityDays	Minimum number of inactivity days in the month for the vessels of the strategy	Real between 0 and 1
		Metier	Metier for which the activity of the month in the strategy is being specified	Metier
		PropMetStrMonth	Proportion of the vessels of the strategy that practice a given metier during a given month	Real between 0 and 1

Table 5. Notations used in the equations (alphabetical order). Whenever the parameter or variable depends on other parameters, these are reported between parentheses.

$CrewShareRate(sov, met)$	Crew share rate for a vessel of set of vessels *sov* practicing metier *met*
$CrewSize(sov, met)$	Crew size for a vessel of set of vessels *sov* practicing metier *met*
$DiscardsPerStrategyMet(str, met, pop, cl, zpop)$	Discards of class *cl* of *pop* in zone *pop* resulting from vessels of *Strategy str* practicing metier *met*
$SF_{std}(gear)$	Standardisation factor for *gear*
$VesselCostsPerYear(sov)$	Fixed costs per year for a vessel of set of vessel *sov*
$FinancialCosts(sov)$	Financial costs of a vessel of set of vessel *sov*
$LandingCostsRate(str, met)$	Landing cost rate linked to metier *met* in the port of strategy *str*
$MinNbInactDays(str, month)$	Minimum Number of Inactivity Days Per Month for strategy *str*
$Duration(month)$	Duration of a given month in days
M(pop,cl)	Instantaneous coefficient of natural mortality for class *cl* of population *pop* (in yr^{-1})
$NbFishOpePerDay(sov, met)$	Number of fishing operations per fishing day for a vessel from the set of vessels sov when practicing metier *met*
$NbGearsPerOpe(sov, met)$	Number of gears used per fishing operation for a vessel from the set of vessels *sov* when practicing metier *met*
$NbVessels(sov)$	Number of vessels in set of vessels *sov*
$OtherSpeciesGrossValue(str, met)$	Gross value arising from catch of species not explicitly modelled for strategy *str* and metier *met*
$OtherRunningCostsPerDay(sov, met)$	Bait and ice costs and crew food costs for a vessel from the set of vessels sov when practicing metier *met*
$PropNbVessels(str)$	Proportion of vessels of the SetOfVessels that are in Strategy *str*
$PropMetStr(str, met, month)$	Proportion of vessels of strategy *str* that practice metier *met* at month
$q(pop, cl, zpop, month)$	Catchability coefficient of class *cl* of population *pop* for month in population zone *zpop*
$GearMaintenanceCostsPerDay(sov, met)$	Repair and maintenance costs per fishing day for a vessel of set of vessel *sov* practicing metier *met*
Sel(gear, pop, cl)	Selectivity of gear for class *cl* of population
$Speed(vt)$	Average speed of a vessel from SetOfVessels *sov*
TargetF(met,pop,month)	Target Factor of metier *met* for population *pop* at month
$TripDuration(str, month)$	Trip Duration of TripType corresponding to strategy *str* at *month*

$UnitFuelCostFishing(sov, met)$	Fuel, oil and ice costs per fishing operation for a vessel of set of vessel *sov* practicing metier *met*
$UnitFuelCostTravel(vt)$	Fuel and oil cost per hour of travel for a vessel of type *vt*

Table 6. Technical characteristics of vessel types.

Vessel type	*Length (m)*	*Speed ($km.h^{-1}$)*	*MaxTripDuration (d)*	*ActivityRange (km)*	*MinCrewSize (nb)*	*UnitFuelCostTravel* (euro.h^{-1})
Medium	*14*	*17.2*	*3*	*100*	*3*	*13*
Large	*18*	*18.5*	*7*	*200*	*4*	*14*

Table 7. Sets of vessels considered in the application and corresponding parameters. Costs are in euros. "Twin" and respectively "single") mean the metier uses twin trawl gear (resp. single trawl gear). "Benthic" means the metier targets benthic fish species.

Set of Vessels (nb)	FixedCostsPerMonth	Metiers practiced	NumberOperationsPerDay	Crew size	Crew Food Cost	Crew Share Rate	GearMaintenanceCosts	Landing CostRate	Other RunningCostsPerDay
Medium vessels from GV (115) Medium vessels from LS (36)	5220.5	BenthicTwin BenthicSingle HakeTwin HakeSingle NephropsTwin NephropsSingle	5	3	23.5	0.45	5.7	0.055	5.18
Large vessels from GV (41) Large vessels from LS (42)	6914.4	BenthicTwin BenthicSingle HakeTwin HakeSingle NephropsTwin NephropsSingle	6	4	43.4	0.43	8.2	0.048	12

Table 8. Parameters for the metiers considered in the application.

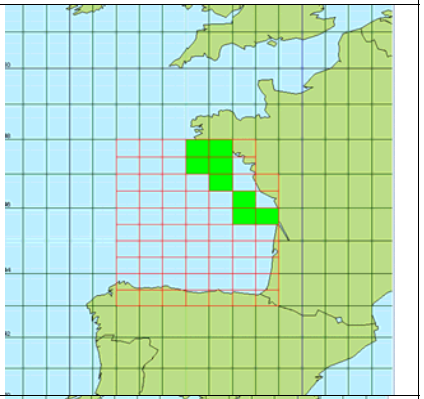
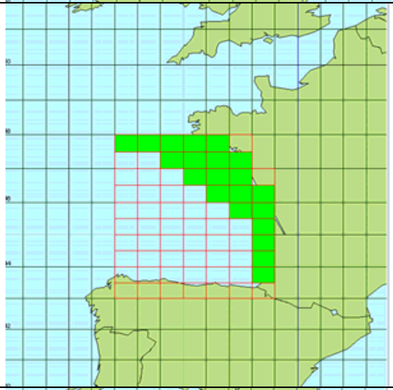
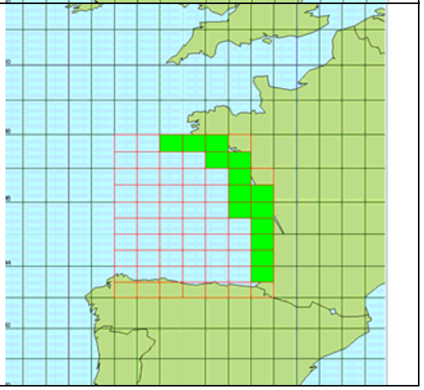
Metier and target factor for Nephrops	Metier zone
NephropsTwin and **NephropsSingle** **Target species: Nephrops** **Target factor 0.74** **Nephrops is primary catch**	
BenthicTwin and **Benthic Single** **Target species: monkfish** **Nephrops target factor 0.07**	
HakeTwin and **HakeSingle** **Target species: hake** **Nephrops target factor 0.14**	

Table 9. Proportions (%) of vessels practising a given metier at a given month for each strategy considered in the application. For a given strategy, proportions do not necessarily sum up to 1 in each column, because vessels may work outside of the fishery. Each set of four strategies in the first column has similar proportions irrespective of ports and vessel size. The number of vessels in each strategy is reported between parentheses. In strategy names, ‘B’, ‘N’ and ‘H’ respectively stand for Benthic, Nephrops and Hake. ‘Med’ and ‘Lar’ respectively stand for Medium and Large.

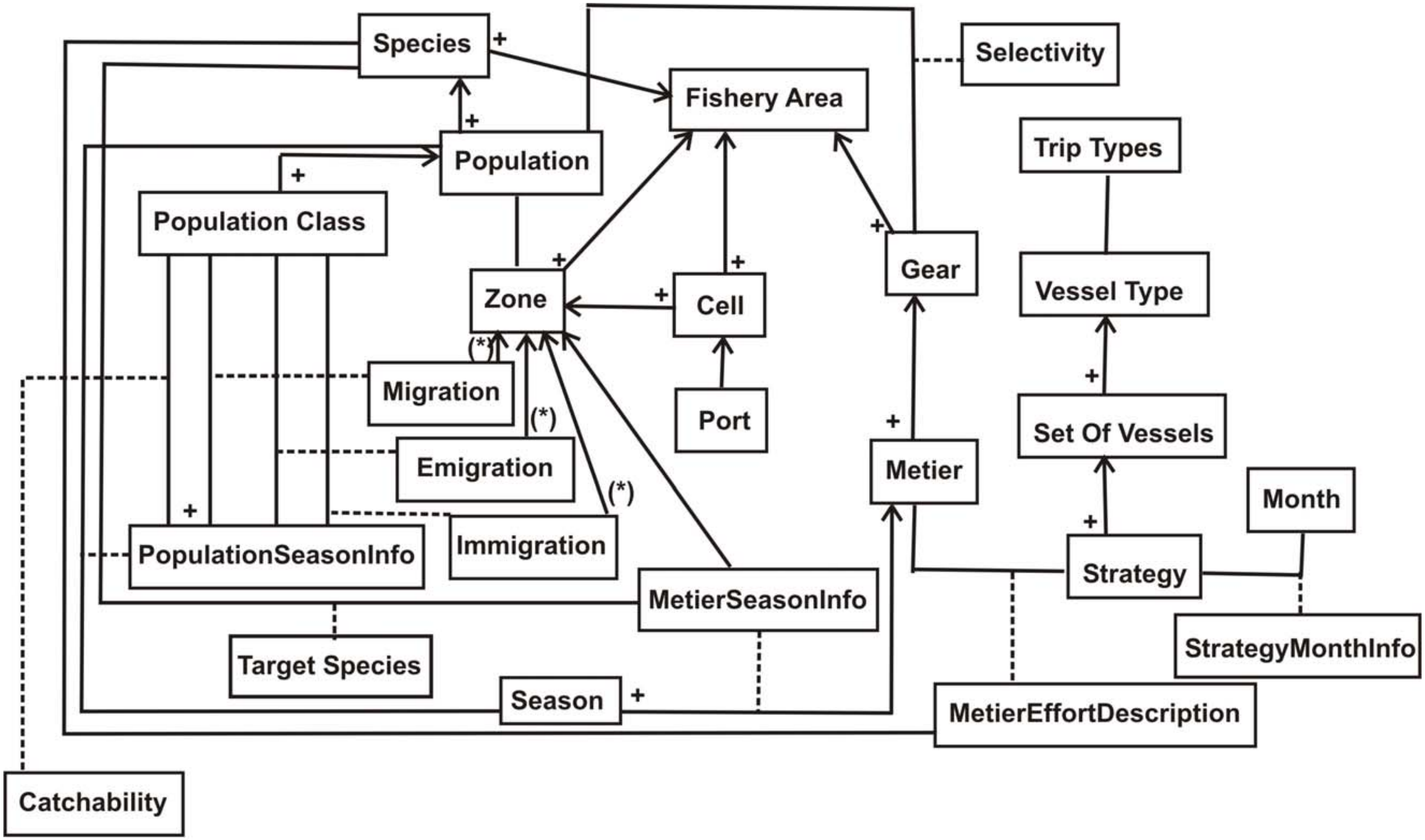
Strategy name (nb)	Metier	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BMedGV (37) BMedLS (14) BLarGV (28) BLarLS (28)	BenthicTwin and BenthicSingle	33	36	38	38	39	38	37	40	43	44	45	40
NMedGV (46) NMedLS (14) NLarGV (7) NLarLS (7)	BenthicTwin and BenthicSingle	14	6	3	1	0	0	0	1	3	9	13	13
	HakeTwin and HakeSingle	27	36	46	48	48	49	48	45	41	34	33	32
	NephropsTwin and NephropsSingle	3	1	0	0	1	1	1	4	3	5	2	3
HMedGV (20) HMedLS (6) HLarGV (7) HLarLS (7)	BenthicTwin and BenthicSingle	9	12	7	10	9	8	7	6	7	8	7	9
	HakeTwin and HakeSingle	0	2	7	11	13	12	9	7	3	3	2	1
	NephropsTwin and NephropsSingle	24	23	19	19	21	27	31	32	35	34	28	22

Table 10. Parameters of the management measures and corresponding fisher's response considered in the application. The fishing unit comprises the vessel and the crew.

Management measure	Fishing units affected by the measure	Fisher's response (at a given month)
No policy	None	None
MPA[1]	Fishing units which metier zone overlaps the MPA	If the MPA encloses the entire metier zone, the fishing unit remains at port. Otherwise, fishing time is uniformly reallocated over the rest of the metier zone that remains open
Twin trawl prohibition	Fishing units which practice metiers using twin trawl	If the strategy of the fishing unit includes other metiers using a non-prohibited gear during the month, then the fishing time of the fishing unit is uniformly reallocated between these metiers. Otherwise the fishing unit remains at port during the month
Nephrops TAC of 900 t	Fishing units which practice metier catching Nephrops	If Nephrops is not a primary catch for the fishing unit, it continues fishing in the same way and discards Nephrops catch. Otherwise the fishing time of the fishing unit is uniformly reallocated within the same strategy, according to the following set of priorities: 1) toward metiers fishing with the same gear but not targetting Nephrops; 2) if there is no such metier, toward metiers fishing with another gear but not targetting Nephrops; 3) if there is no such metier, the fishing unit remains at port during the month.

[1] ***permanent closure of two rectangles in subdivision VIIIa, south of Le Guilvinec.***

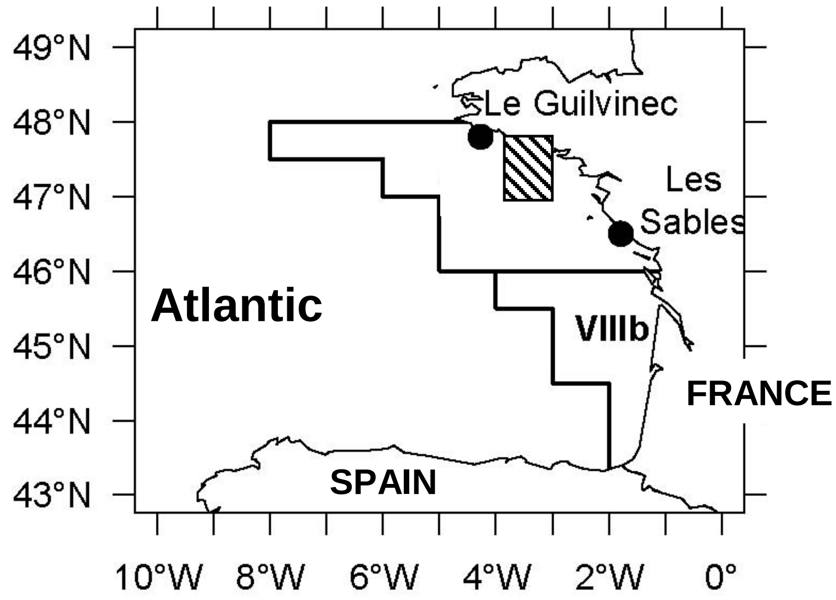
Figures



(*) Departure Area - Arrival Area

Figure 1. Class diagram for ISIS-Fish model version 3.0. For sake of concision, object attributes were not detailed on the diagram; they are reported on Table 2. These objects may not fully match those of Table 1, which correspond to objects stored in the database attached to ISIS-Fish. A “+” sign indicates a cardinality equal to or larger than 1, e.g. a port is in only one cell, but a cell may comprise several ports.

Figure 2. The Bay of Biscay area with ICES subdivisions VIIIa and b, and ports of Le Guilvinec and Les Sables. Subdivisions VIIIa and b encompass the continental shelf of the Bay of Biscay where the mixed fishery takes place. The hatched area corresponds to the closed area.



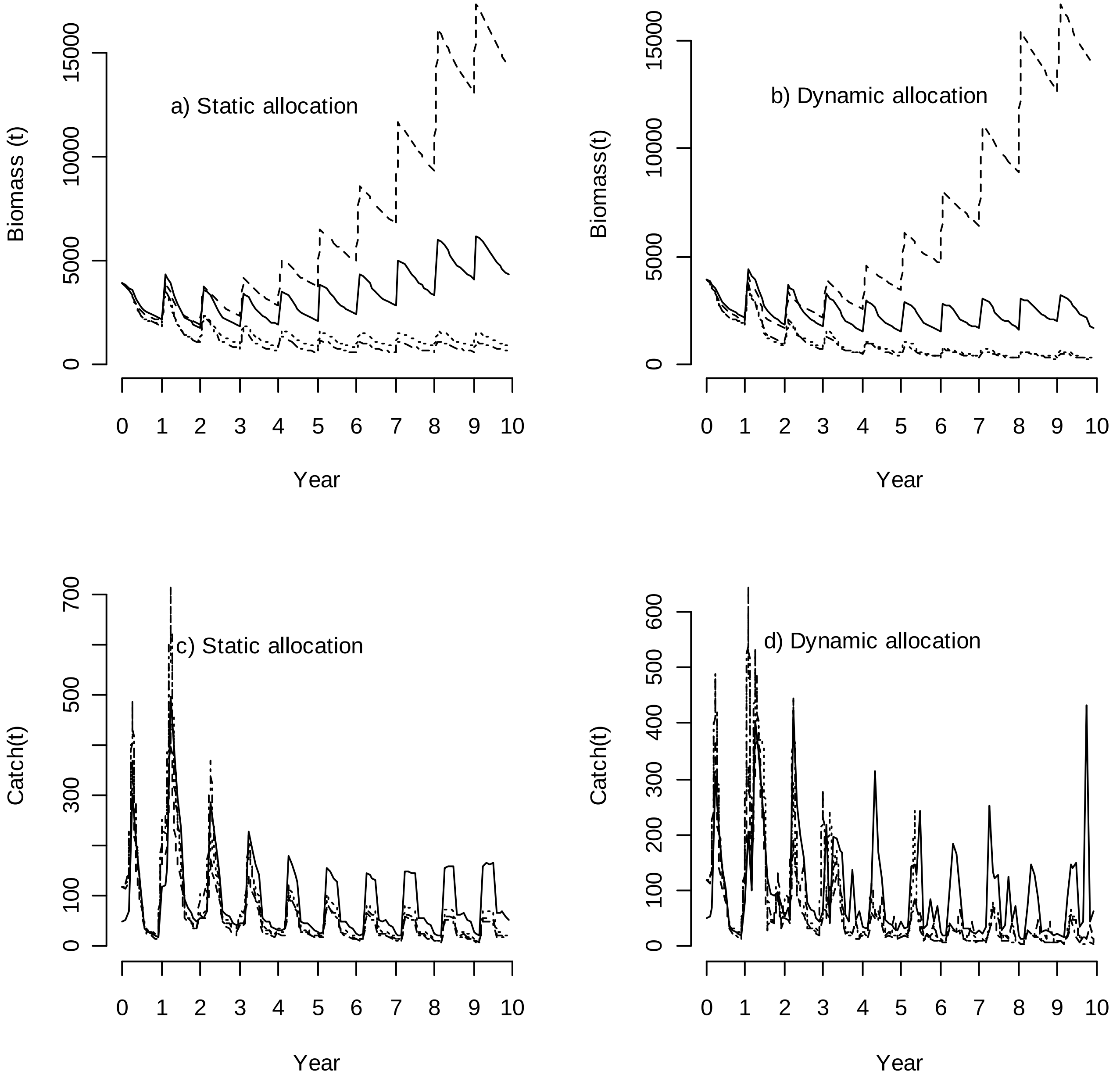


Figure 3. Trajectories of Nephrops biomass and catch for each management measure simulated in the case of a static allocation of fishing effort over metiers (biomass in a) and catch in c)), and b) a dynamic fishing effort allocation according to a gravity model (biomass in b) and catch in d)). The line type for each management measure is as follows: filled line (MPA), dashed line (No Policy), dotted line (TAC) and broken line (Twin trawl ban).

Figure 4

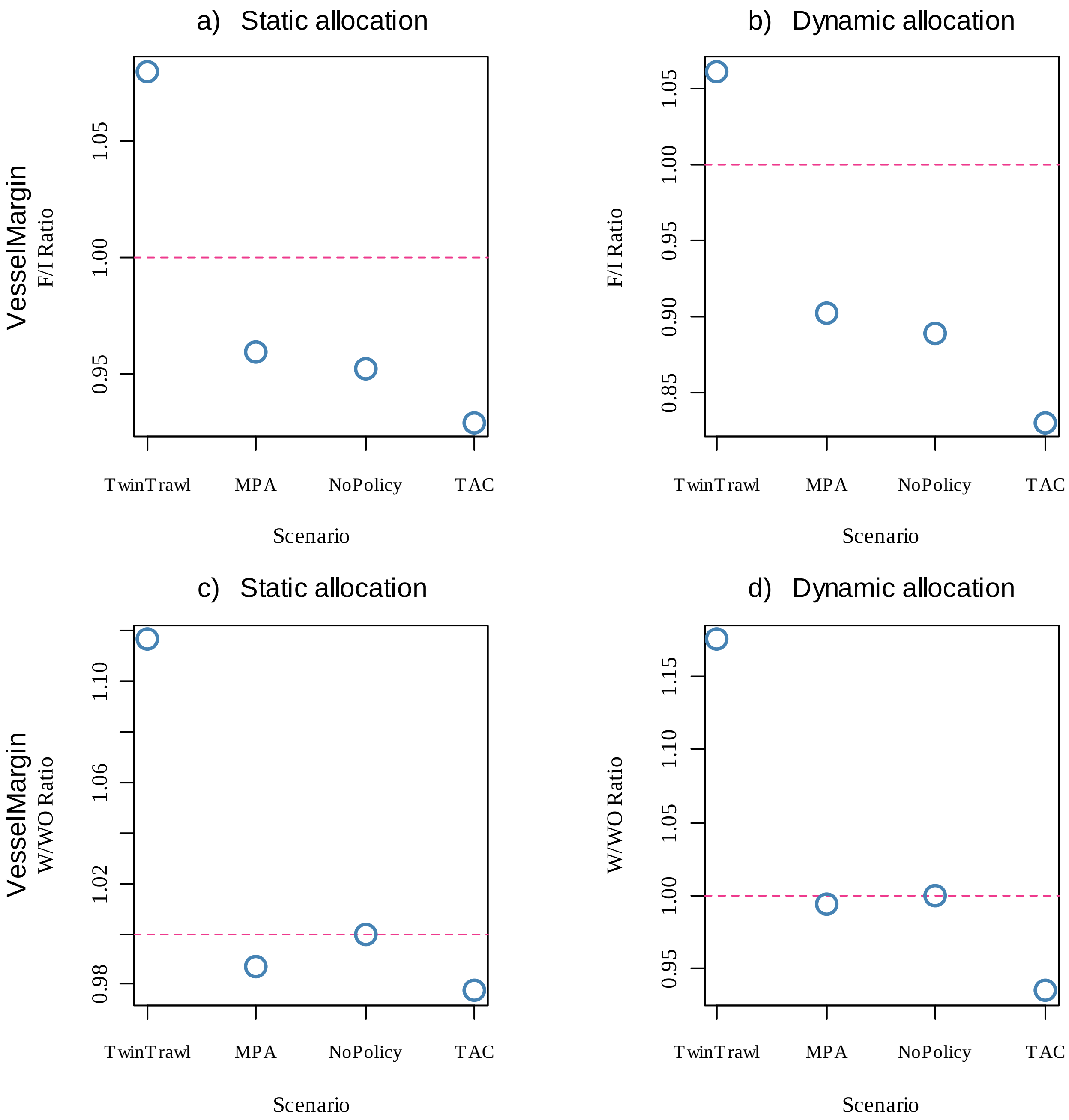


Figure 4. Ratios of vessel margins. F/I ratio corresponds to vessel margin at the end of simulation over vessel Margin at the beginning of simulation for each management measure in the case of a) a static allocation of fishing effort over metiers, and b) a dynamic fishing effort allocation according to a gravity model. W/WO ratio corresponds to vessel margin under a given policy divided by vessel margin under the “No Policy” option in the case of c) a static allocation of fishing effort over metiers, and d) a dynamic fishing effort allocation according to a gravity model. Equations for ratios are given in Eq. (43).

Figure 5

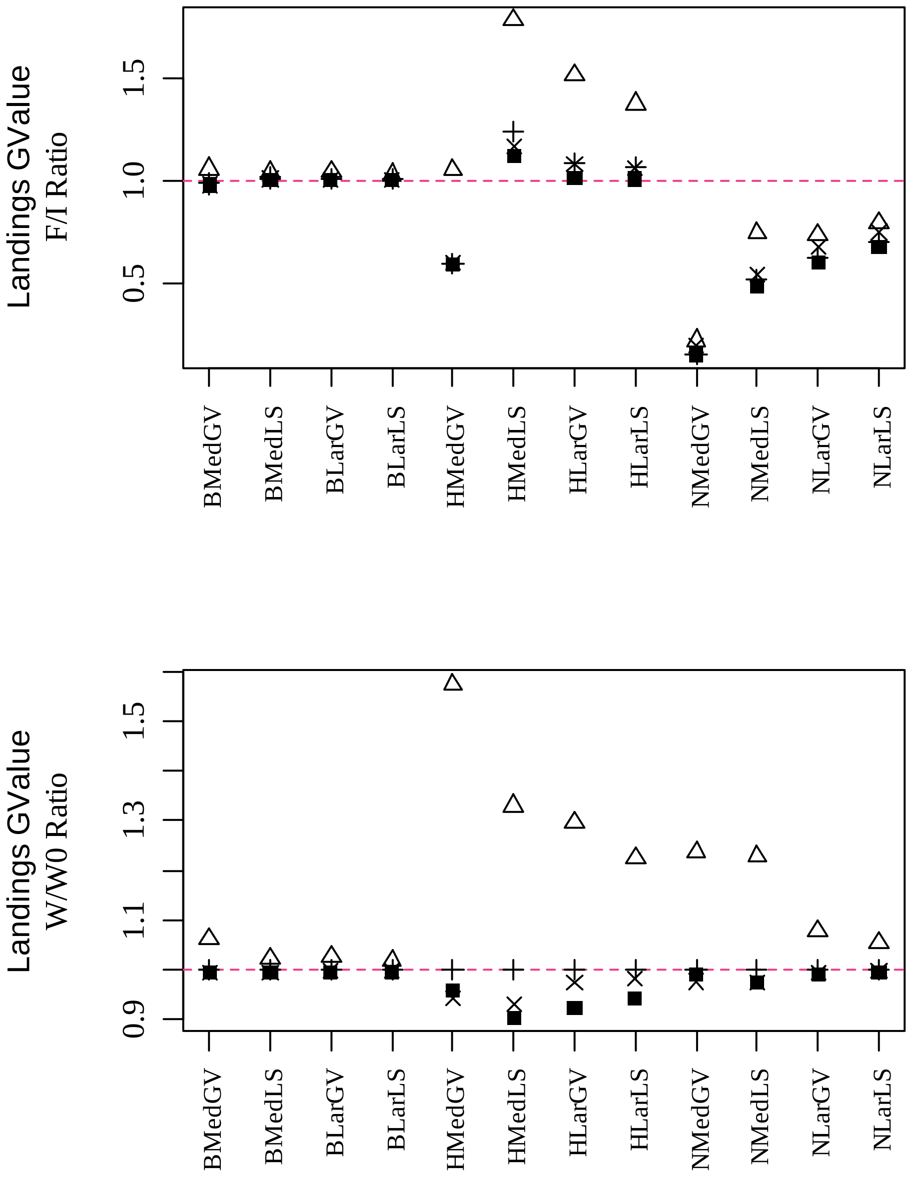


Figure 5. Ratios of gross value of landings in the case of a static allocation of fishing effort. The F/I ratio (top) corresponds to the gross value of landings at the end of simulation divided by the gross value of landings at the beginning of simulation for each strategy (on x-axis) and for each management measure simulated (△=MPA, ×=No Policy, +=TAC, ■=Twin trawl ban). Similarly, the W/WO ratio (bottom) corresponds to the gross value of landings under a given policy divided by the gross value of landings under the “No Policy” option. Strategy code is defined in Table 9.