Simulating the short-term response of fisheries to regulatory controls: a multi agent approach

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Abstract: Understanding the dynamics of fishing effort plays a key role in predicting the impacts of regulatory measures on fisheries. In recent years, there has been a growing interest in the use of bio-economic models to represent and analyze the short-term dynamics of fishing effort in response to regulation, in the fisheries management literature. In this literature, fishing firms are usually modeled as autonomous decision units determining their harvest strategies so as to maximize profit given technical and institutional constraints. The overall dynamics of a fishery is modeled as the result of these individual choices, and of interactions between individual choices due to the impacts of harvesting on the fish stock, and/or to problems of congestion. Applications have, for example, been related to the discussion of marine protected areas as fisheries management tools. The paper presents a multi-agent model of a fishery targeting different species in different areas, with different types of gear. The model is based on the Cormas platform developed for the simulation of the dynamics of common resource systems. Simulation results are presented to illustrate how the model can be used to analyze the consequences of regulatory measures such as temporary or permanent fishing bans on the allocation of fishing effort between target species and areas, and the associated economic impacts.

Keywords: *Fisheries dynamics, Fishing ban, Bio-Economic Modeling, Multi-Agent Simulation*

1. INTRODUCTION

Recently, there has been growing interest in fisheries management literature in the use of bio-economic models to represent and analyze the short-term dynamics of fishing effort in response to regulation. An implication for modeling is the greater degree of complexity that needs to be taken into account in the formal representation and analysis of the biological and economic dynamics of fisheries. Various modeling techniques have been used. Both optimization and system dynamics simulation techniques have been applied to fairly simple descriptions of the spatial and temporal evolution of fishing effort such as in single-species, single-fleet, multi-zone models (see e.g. Anderson (2002), Sanchirico and Wilen (1999)), or multi-species, single-fleet, multi-zone models (see e.g. Boncoeur et al (2002)). Optimization techniques have also been used in more complex bio-economic models involving several species caught by several fleets in several different zones (Collins et al., 1998).

By focusing on individual, rather than global interactions, agent-based modeling appears as an interesting approach to this type of modeling. In particular, it allows the modeling of relatively complex systems while keeping with a simulation approach, making the explicit representation and analysis of the evolution of these systems possible, both globally and with a fairly high degree of detail.

In what follows, a multi-agent model of a fishery in which a single fleet targets different species on different fishing grounds with different types of gear is presented. We use the simulation approach developed by Sanchirico and Wilen (1999) to represent the evolution of a fishery harvesting a fish population allocated into biologically interdependent patches. Following Collins et al. (1998), we add the possibility for the fishing fleet to target different species on each ground.

2. THE MODEL

The fishery is composed of a fleet of polyvalent and mobile vessels, operating over an area A, divided into j zones. The harvested resource is composed of a set of i target species, with no biological interactions. Each species is distributed over the entire area, in local stocks characterized by:

- Their biomass X_{ij};
- A species specific intrinsic growth rate of the biomass r_{ij} (than can vary according to the zone);

- A species-specific diffusion coefficient $d_{ijj'}$ between connective zones *j* and *j'*.

Each zone is characterized by a local carrying capacity $X_{ij}^{\max}$ for each species.

The following notations are used to describe the nominal fishing effort allocated to each option at each time step:

- E_{ij} is the standard nominal fishing effort targeting species i in zone j (hereafter called "métier");
- q_{ij} is a capturability coefficient for species i in zone j per unit of standard nominal effort;
- c_i is the operational harvesting cost per unit of effort targeting species i in zone j;
- p_i is the fixed unit price of catch per species

2.1. Stock dynamics

The dynamics of stocks is modeled as follows:

$$\frac{dX_{ij}}{dt} = f_{ij}(X_{ij})X_{ij} + T_{ijj'} - Y_{ij} \tag{1}$$

where $f_{ij}(X_{ij})$ measures the instantaneous growth per unit of biomass of species i in zone j, $T_{ijj'}$ measures the migration of biomass of species i between zone j and $j'(j' \neq j)$, and Y_{ij} measures the instantaneous catch of species i in zone j.

An instantaneous growth function of the logistic form is assumed for the stocks:

$$f_{ij}(X_{ij}) = r_{ij}\left(1 - \frac{X_{ij}}{X_{ij}^{\max}}\right) \tag{2}$$

Instantaneous catch per unit of effort is considered as directly proportional to nominal fishing effort E_{ij} and to the local abundance of the target species:

$$Y_{ij} = q_{ij}E_{ij}X_{ij} \tag{3}$$

Net transfer of biomass of species i between zone j and a connective zone j' is assumed to be density-dependent. It is modeled as a function of the difference between the ratio of biomass of each stock to its carrying capacity in zone j and in zone j':

$$T_{ijj'} = d_{ijj'}\left(\frac{X_{ij}}{X_{ij}^{\max}} - \frac{X_{ij'}}{X_{ij'}^{\max}}\right) \tag{4}$$

2.2. Fishing effort dynamics

The aim of the model being to simulate the short term dynamics of fishing activity, maximum fishing effort available in the fishery is considered fixed and the focus in on its allocation between alternative métiers at each time step.

Representation of the dynamics of fishing effort is based on the assumption that the fleet allocates its activity between métiers based on the anticipated short-term profit (margin over variable costs) associated to each métier.

The decision tree that determines, at each time step, the dynamics of fishing effort is represented in the graph below. At each time step, effort units are reallocated to different métiers only if this allows an expected increase in the margin per unit of effort. In other cases, there is no reallocation, and fishing units may remain inactive if the anticipated profits of fishing are negative.

The capacity of effort units to transfer from one zone and/or species to another is described by the following coefficients:

- n a polyvalence coefficient describing the capacity of fishing units to transfer from one target species to another;
- m a spatial mobility coefficient describing the capacity of fishing units to transfer from an exploited zone to another.

Where effort re-allocation takes place, effort dynamics are defined by the equation below:

$$\begin{aligned} \frac{dE_{ij}}{dt} = \; & m\left(g_{ij} - g_{ij'}\right) \\ & + n\left(g_{ij} - g_{i'j}\right) \\ & + m\,n\left(g_{ij} - g_{i'j'}\right) \end{aligned} \tag{5}$$

where g is the anticipated value (at t) of the margin per unit of effort associated to each métier.

Fleet behavior is assumed to be "myopic" in this version of the model: anticipated margins per métier are supposed equal to the margins observed at the previous time step, corrected for the additional costs associated to the selection of a new fishing zone.

$$g_t = \frac{M_{ij}^{\exp}}{E_{ij,t-1}} \tag{6}$$

and

$$M_{ij}^{\exp} = p_i Y_{ij} - \left[1 + \gamma_{jj'}\right] c_i E_{ij} \tag{7}$$

based on $t-1$ observed values. $0 \le \gamma_{jj'} \le 1$ is the additional cost per unit of effort linked to a change of fishing zone, and depends on the distance between zones.

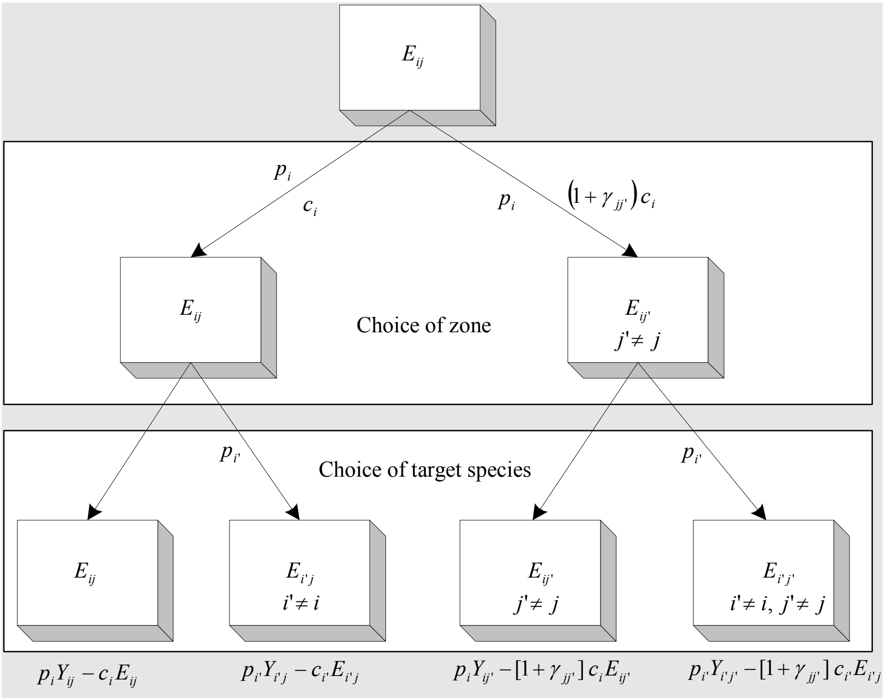

Figure 1. Decision tree of effort re-allocation options

3. APPLICATION TO THE SIMULATION OF A TEMPORARY FISHING BAN ON A 4 ZONE, 2 SPECIES FISHERY

A detailed presentation of the conceptual model and its implementation under Cormas is available in Soulié and Thébaud (2003).

A first application of the model was developed for a simple case of a theoretical "multi-métier" fishery in order to simulate the consequences of a temporary fishing ban

The fishery develops on four zones, targeting two independent species both having density-dependent diffusion processes (Figure 2).

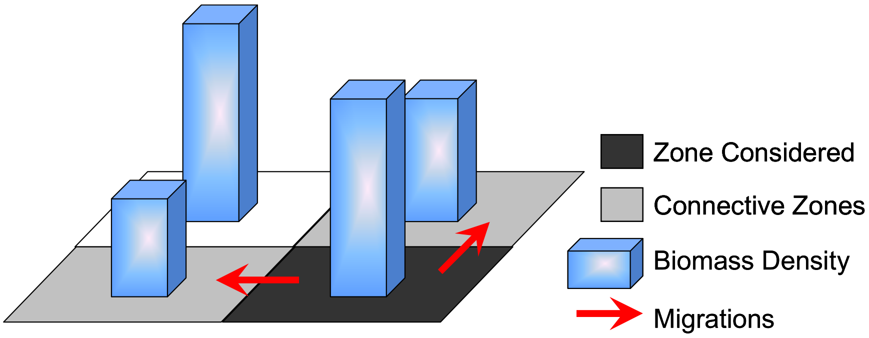

Figure 2. Biomass diffusion in the four-zone model

Global nominal fishing effort and its initial allocation between zones and species (*i.e.* effort per métier) are fixed.

At each time step, nominal fishing effort in each métier can be reallocated to any of the seven other métiers. Additional costs associated to the change of zone vary with the zone towards which movement is being considered. In this application, costs of moving horizontally or vertically are assumed to be lower than costs of moving along the diagonal of the area (see parameters value below).

3.1. Experimental design

First, a sensitivity analysis of the model to the level of fishing effort allocated to the different species and areas is carried out, in order to determine the steady state equilibrium of the fishery with and without area closures, given the parameter values below. Simulations are run for 300 time steps. A first run is carried out without a fishing ban. The second run is carried out assuming that a ban occurs on the catch of one of the species in zone 1 between time step 10 and 100. A third run is carried out assuming that the fishing ban applies to the two species in area 1. The levels of short-term profits in the fishery are then compared for cases with and without the area closure, in present-value terms.

Table 1. Parameter values used in the first run

Biological Parameters	**Species 1**	**Species 2**
Carrying capacities	10	10
Growth rates	0.8	0.8
Fish diffusion coefficients	0.2	0.2
Economic parameters		
Fish prices	10	10
Unit costs of effort	3	3
Technical parameters		
Polyvalence rates	0.0004	0.0004
Effort mobility coefficients	0.0004	0.0004
Spatial penalties	0.1 for horiz./vertical move; 0.2 for diag. move	

Second, nominal fishing effort is fixed at a level allowing positive margins over variables costs throughout the fishery. Simulations are run for 300 time steps, with the fishing ban. Two cases are considered: in a first run, fishing units affected by the ban are forced to remain inactive during the ban; in a second run, these units are allowed to reallocate themselves freely between métiers. Analysis of the results is in terms of the dynamic response of fishing effort to the fishing ban and the overall economic consequences for the fishery over simulation time, as compared to the situation without a ban, in present-value terms.

Third, a sensitivity analysis of the results to the value of the polyvalence and the mobility parameters is carried out. Again, simulations are run for 300 time steps with the fishing ban on one métier between time step 10 and time step 100. Sensitivity runs are carried out for different initial equilibrium levels of fishing effort and fish biomass, identified based on stage 1 simulation results. Analysis of the results is in term of the global economic costs of the fishing ban as compared to a situation without a ban.

3.2. Simulation results

Stage 1 – Equilibrium short-term profits as a function of fishing effort

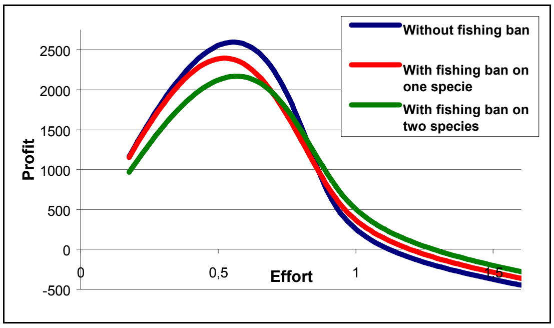

Figure 2. Steady-state short-term profit with and without a fishing ban

The fishing ban causes a reduction of the steady-state short-term profits that can be derived from the fishery globally, for low to medium levels of fishing effort. This reduction is more important for a complete, rather than partial, ban. For high levels of effort (corresponding to situations of excess capacity in the fishery), the fishing ban can cause a slight increase in global profits at a fixed level of effort. Additionally, the fishery can continue to derive positive short-term profits for higher levels of fishing effort with a fishing ban in place. This is due to the reserve effect: during the ban, the protected biomass is allowed to grow and diffuse to connective zones, allowing an increase in catches per unit of effort, and an increase in effort in these zones while the supporting biomass is protected from direct harvesting.

Stage 2 – Dynamic response to a fishing ban

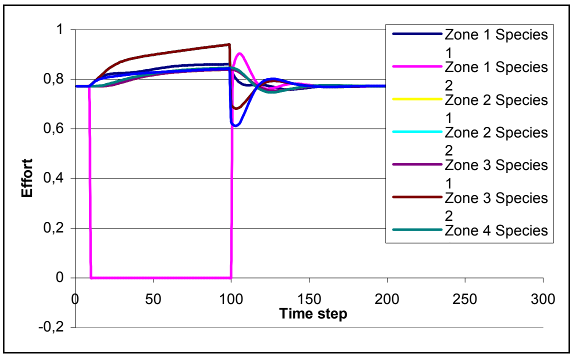

Figure 3. Dynamic response of the fishery

The fishing ban on species 2 in zone 1 drives effort devoted to this métier to 0. This effort is partially transferred to the other métiers: spatial mobility of fishing units leads to increased effort targeting species 2 in zones 2, 3 and 4, and to a lesser extent to an increase in effort targeting species 1 in all zones.

When the fishing ban ends, zone 1 becomes very attractive as the stock of species 2 it shelters has been allowed to rebuild. Large transfers of effort in favor of this species/zone alternative thus take place, leading to a rapid decline in biomass and catch per unit of effort, followed by the exit of fishing units. After another smaller oscillation, the system returns to its initial equilibrium state.

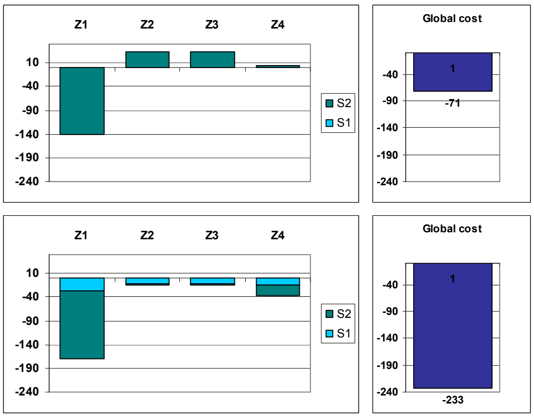

Figure 4. Costs per métier and global costs of the fishing ban (Z = zone; S = species)

The top graphs in figure 4 show the global cost and the cost per métier of the fishing ban without effort reallocation. In this case, the cost is fully supported by the métier at which the fishing ban is directed. Fishing for species 2 in the other zones even benefits from the ban due to the reserve effect, although the more distant zone only benefits indirectly from this effect. Fishing for species 1 is not affected.

The bottom graphs in figure 4 shows the global cost and the cost per métier of the fishing ban with effort reallocation. Simulation results illustrate two consequences of the fishing ban. First, the global cost of the fishing ban is more than 3 times higher than without reallocation of effort. The response of the fishing fleet tends to increase the global impact of the ban. Second and correlatively, this cost is distributed throughout the fishery, affecting the catch of the two species in the four zones. None of the métiers benefit from the fishing ban, since effort units tend to move to alternatives where higher profits can be made until all such alternatives are extinguished. The impact on zone 1 is greater, since part of the affected fishing units shift to targeting species 1, entailing a drop in short-term profit derived from this métier. Zone 4 being more affected than zones 2 and 3 is a consequence of the dynamics of the system during and after the fishing ban. Initially, units of effort flow from the protected zone to its immediate neighbors (zones 2 and 3). As a consequence, these become less attractive than zone 4, and effort tends to flow towards this more distant zone. At the end of the fishing ban, zone 4 being more distant is the last to benefit from a transfer of fishing effort back towards zone 1.

Stage 3 – Sensitivity Analysis

Sensitivity analysis of model results was carried out by varying the key biological and technical parameters simultaneously over repeated runs, with and without a ban, for various initial levels of fishing effort in the fishery. Only parts of the results are presented below, to illustrate the varying importance of the effort reallocation issue depending on the status of the fishery under study.

The left graph in Figure 5 represents the case of an under-exploited fishery. In this case, effort reallocation serves to minimize the costs of the fishing ban, as it allows the fishing fleet to take advantage of harvest potentials in other zones for the same species, and in all zones for the other species. The cost of the ban remains positive, but can be *lowered* by effort reallocation, with the consequence that it will be spread throughout the fishery, rather than concentrated on a single métier.

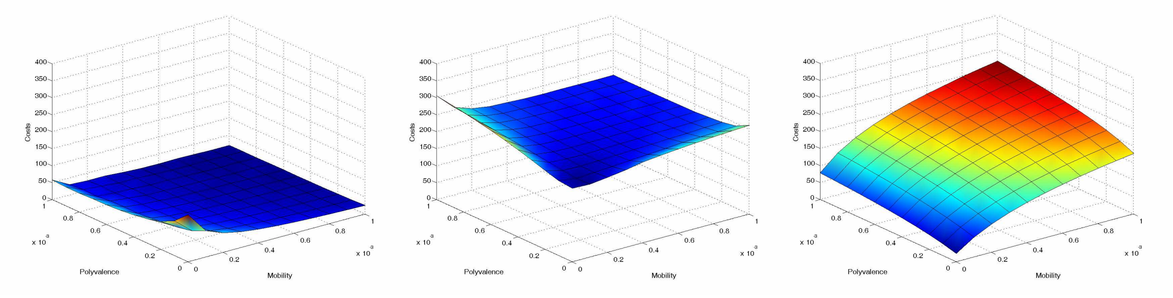

Figure 5. Area covered by the costs when mobility and polyvalence increase at a given effort level

The middle graph in figure 5 represents the case of a fishery exploited at the maximum short-term economic yield. The cost of the fishing ban is higher in comparison with the previous case. In this case, effort reallocation has a limited impact on the total cost of the ban if the fleet is both mobile and polyvalent. However, it increases the cost of the ban if the fleet is only mobile, or only polyvalent, as this limits the capacity of fishing units to take advantage of changes in local stock abundances.

The graph on the right in figure 5 represents the case of an over-harvested fishery. Sensivity of the impacts of the ban to the capacity of the fleet to reallocate its fishing effort is much greater in this case. While if no effort is reallocated, the global cost of the ban is fairly low, this rises quickly with increasing polyvalence and/or mobility of fishing units.

4. CONCLUSION

The main purpose of this exercise was to develop a multi-agent system to simulate the dynamics of fisheries from a short-term, bio economic point of view. Although the fishery modeled in this paper is purely theoretical, simulation results can be used to discuss a number of issues that usually arise in debates on the economic impacts of fishing bans in real-life fisheries management, whether these bans are related to resource management considerations or to pollution problems.

The multi-agent approach allows studying the response of fishing effort to changes in regulation at each time step, given the assumptions made on the behavior of fishing units. The application to a fairly simple case shows the great complexity of such dynamics, with the response of fishing effort and of fish biomasses combining in complicated cascade effects between métiers. Overall evaluation of the economic impacts of a fishing ban as a function of the capacity of the fleet to adapt itself, in this model, shows the importance of taking such dynamics into account in the analysis of the expected consequences of regulatory measures in fisheries.

The model as it stands can be used to simulate different cases, from the fully mobile fleet harvesting relatively sedentary resources to the sedentary fleets harvesting highly migratory stocks (sequential fisheries), as well as any intermediate situation. Spatial heterogeneity in fleet characteristics can also be introduced, particularly as regards the capacity to reallocate its effort. The model being entirely initialized by an XML file (Soulié and Thébaud, 2003), it is possible to rapidly develop and analyze various scenarios.

Work in progress involves extending this theoretical model to include the possibility to individualize several fleets with different characteristics, both technical and behavioral, as well as developing applied models based on the same general representation of effort dynamics, but making use of real-life geo-referenced data. Applications concern the Bay of Biscay fisheries off the coast of France.

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