Fishing Through Fish Communities: A Simple Bio-economic Model

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ABSTRACT

Recent work in the domain of fisheries ecology has shown that major changes occur in fish communities exploited by commercial fisheries. Selective fishing pressure on the more highly valued components of fish communities is amongst the key factors proposed to explain these changes. Under de facto open access conditions, it is suggested that sequential over harvesting of higher valued fish and/or fish species leads to modifications in the structure of both fish communities, and fisheries landings. This poses the question of the economic drivers of such sequential over-harvesting, and the implications of this process in terms of the total value of landings from a given fish community.

The aim of this paper is to present an analysis of this question using a simple bio-economic model of an open access fishery targeting different species. The model is used to analyse the process by which harvesting of the set of species develops, given differences in the economic and biological characteristics of these species. Sensitivity to these differences of both development paths and steady state equilibrium of the fishery are analysed. Simulation results show that, where total effort is controlled but its allocation between alternative species may occur freely (a case of "regulated open access"), there may be significant consequences in terms of the biological status of stocks, and in terms of potential maximum rents. This work is carried out as part of the "CHALOUPE" research project, funded by the French National Research Agency (http://www.projet-chaloupe.fr).

1. INTRODUCTION

Recent work in the domain of fisheries ecology has shown that major changes occur in the composition of landings of many commercial fisheries (Pauly et al., 1998). Selective fishing pressure on more highly valued components of fish communities, and its indirect effects via trophic interactions, are amongst the key factors proposed to explain these changes. In this work, sequential over-harvesting of higher valued fish, corresponding to higher trophic levels, and their replacement by less valuable lower-trophic-level species in fish communities, is thus seen as a key driver of the long-term modifications in the structure fisheries landings. An alternative interpretation of these modifications is that they are due to the sequential addition of lower-trophic-level species to continued, although possibly reduced, landings of higher-trophic-level species (Essington et al., 2006), thus referring to a "fishing through the food web" process.

The economic dimensions of sequential harvesting and its implications have led to the development of empirical research, looking at observed changes in fisheries landings, in both volume and value terms. Sumaïla (1998) presented an analysis based on FAO marine fisheries catch data collected from all fishing nations for 1950 to 1996 for over 1000 species of fish. Pinnegar et al. (2002) analysed modifications in the composition of landings and relative prices of 26 species caught in the Celtic Sea from the years 1970 to 2000. A further analysis of this fishery, and comparison with Italian data on fisheries landings for 33 species over the same period was carried out by Pinnegar et al. (2006). Steinmetz et al. (2006) analysed changes in the composition of landings by French fleets operating in the North-East Atlantic over the same period, and also showed a change in composition of these landings, as well as major changes in their value.

In this paper, we develop a simple bio-economic model of a multi-species fishery and use it to analyse the process of sequential harvesting of different species. The paper is structured as follows: the model is presented in section 2; simulation protocols are presented in section 3, and simulation results in section 4. Section 5 concludes.

2. THE MODEL

Details of the model are presented in Soulié and Thébaud (2006). The fishery is composed of a fleet of mobile vessels targeting multiple species (e.g. polyvalent), 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 $X_{i,j}$;
- An intrinsic natural growth rate $r_{i,j}$;
- A spatial mobility coefficient $d_{i,j,j'}$;
- A carrying capacity $X_{i,j}^{\max}$ for each species in each zone (each stock).

The concept of métier is introduced to describe the set of fishing options available to the fleet. A métier is defined as the choice to target a particular species in a particular zone, with a given level of productivity. The following notations are used to describe nominal fishing effort allocated to each métier at each time step, and the associated technical, cost and price parameters:

- $E_{i,j}$ the fishing effort targeting species i in zone j;
- $q_{i,j}$ a catchability coefficient for species i in zone j per unit of effort;
- $c_{i,j}$ the unit cost of effort;
- p_i the fixed unit price per species.

2.1. Stock dynamics

The dynamics of stocks are modelled as follows:

$$X_{i,j}(t+\Delta t) = X_{i,j}(t) + \left(\begin{array}{l} f_{i,j}\left(X_{i,j}(t)\right) X_{i,j}(t) + \\ \sum_{j' \neq j} S_{i,j,j'}(t) - Y_{i,j}(t) \end{array} \right) \Delta t \qquad (1)$$

Where $f_{i,j}\left(X_{i,j}(t)\right)$ measures the instantaneous growth per unit of biomass of species i in zone j, $S_{i,j,j'}$ measures the migration of biomass of species i between zone j and $j'(j \neq j')$, and $Y_{i,j}(t)$ measures the catch of species i in zone j.

A logistic growth function is assumed for the stocks:

$$f_{i,j}\left(X_{i,j}(t)\right) = r_{i,j}\left(1 - \frac{X_{i,j}(t)}{X_{i,j}^{\max}}\right) \qquad (2)$$

Instantaneous catch per unit of effort in each zone is considered as directly proportional to fishing effort $E_{i,j}$ and to the local abundance of the target species:

$$Y_{i,j}(t) = q_{i,j} E_{i,j}(t) X_{i,j}(t) \qquad (3)$$

The net transfer of biomass of species i between zone j and a connective zone j' is assumed to be density-dependent:

$$S_{i,j,j'}(t) = d_{i,j,j'}\left(\frac{X_{i,j'}(t)}{X_{i,j'}^{\max}} - \frac{X_{i,j}(t)}{X_{i,j}^{\max}}\right) \qquad (4)$$

with $d_{i,j,j'}$ a coefficient describing the mobility of the species. No biological interaction (competition, predation) between species is included in the model, hence any sequential harvesting observed here can only be due to a “fishing through” the fish community process.

2.2. Fishing effort dynamics

Representation of the dynamics of fishing effort is based on the assumption that the fleet allocates its activity between métiers based on the anticipated margin over variable costs associated with each métier[1].

Units of effort will be reallocated to métiers different from their current métier if this allows an increase in the anticipated margin per unit of effort. In all other cases, no effort reallocation will occur (and some units of effort may remain inactive where only negative anticipated margins prevail).

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

[1] Effort allocation in the system is modelled at the level of metiers, and operated on the basis of an agent-based representation of zones. Hence, individual vessel choices are not explicitly modelled.

- 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 one zone to another.

An adaptive anticipations framework with perfect information is used to model the calculation of anticipated margins and allocated effort. Myopic behaviour of the fleet is assumed: anticipated margins per métier are supposed equal to the margins observed at the previous time step, corrected by the additional costs associated with the selection of a new fishing zone. Anticipated margins per metier thus write

$$M_{i,j,i',j'}^{\exp}(t) = p_{i'} q_{i',j} X_{i',j'}(t) - [1 + \gamma_{j,j'}] c_{i'} \quad (5)$$

with $p_{i'}$ the price of species i', $q_{i',j}$ the catchability of species i' in zone j, $c_{i'}$ the unit cost of catching species i' in zone j and a coefficient measuring the extra cost of moving zones, $0 \le \gamma_{j,j'} \le 1$ depending on the distance between zones.

The allocation of effort is based on margins per unit of effort, defined as follows:

$$g_{i,j}(t) = \frac{M_{i,j}^{\exp}(t)}{E_{i,j}(t)} \quad (6)$$

Effort moves from one metier (i.e. from one combination of species-zone) to another according to the following process:

$$E_{i,j}(t + \Delta t) = E_{i,j}(t) + \begin{bmatrix} \sum_{i' \neq i} nT_{i,j,i',j}(t) & + \\ \sum_{j' \neq j} mT_{i,j,i,j'}(t) & + \\ \sum_{i' \neq i, j' \neq j} nmT_{i,j,i',j'}(t) & \end{bmatrix} \Delta t \quad (7)$$

$$T_{i,j,i',j'} = \begin{cases} -\left(g_{i,j,p}(t) - g_{i',j',p}(t)\right) if > 0 \\ 0 \text{ otherwise} \end{cases} \quad (8)$$

The model was developed using the CORMAS modelling platform[2].

3. SIMULATIONS

The model is applied to the case with two species and only one zone, as spatial dynamics are not the primary emphasis here (see Soulié and Thébaud, 2006 for an application to the case with two species and four zones). First, simulations are carried out for different parameter sets in a dynamic framework, so as to reproduce the sequential harvesting of species and test sensitivity of the sequence to biological parameters of the two species. Second, analysis of the steady-state equilibrium of the fishery for different effort levels is carried out, and the sensitivity of this equilibrium to assumptions as regards the relative price of the two species is analyzed.

3.1. Dynamics

We assume here that the fishery is fully open access; hence effort will flow in and out of the fishery freely, in direct relation with its average profitability. If positive margins per unit of effort occur, effort will enter the fishery, while effort will exit if margins are negative.

As described supra, effort can also freely redistribute between species and areas, hence we assume that no access regulation exists at the species and/or metier level.

In order to observe the impact on the dynamics of the fishery of biological assumptions regarding the two species, two different scenarios are considered: (i) first, we consider the case with two species with similar biological parameters but different economic parameters (the price of one species is ten time lower than the price of the other); (ii) second, we consider the case with two species having differences in both biological and economic parameters (the natural growth rate of the highly valued species is three times lower than that of the other species). In both cases, the capacity for fishing effort to reallocate itself between species and areas is the same. At the beginning of the simulation, we assume that both species are almost unexploited, with only a limited amount of effort introduced at step 1. Table 1 gives the parameter values used in the simulations.

Table 1. Parameter values for simulation of dynamics of the fishery

Biological parameters	**Species 1**	**Species 2**
Carrying capacities	10	10 / 3
Growth rates	0.6	0.6 / 0.2
Economic parameters		
Fish prices	1	10
Catch costs per unit	3	3
Technical parameters		
Polyvalence rates	0.0004	

[2] http://cormas.cirad.fr/

3.2. Steady state equilibrium analysis

In this set of simulation runs, it is assumed that total effort levels in the fishery can be controlled, but that it is not possible to control the amount of effort that is dedicated to either species or areas. Hence, while total effort is fixed, the reallocation process described above operates freely. Simulations are carried out in order to identify the equilibrium states of the fishery for different levels of fishing effort and different assumptions regarding the relative prices of the two species: sensitivity runs are carried out for a ratio of the two fish prices varying between 0 and 1. The simulations are carried out for the two scenarios considered in the previous runs regarding biological differences between the two species. Table 2 provides the parameter values used in simulation runs.

Table 2. Parameter values used in simulations of the steady state equilibrium of the fishery

Biological parameters	**Species 1**	**Species 2**
Carrying capacities	10	10 / 3
Growth rates	0.6	0.6 / 0.2
Economic parameters		
Fish prices	Variable	10
Catch costs per unit	3	3
Technical parameters		
Polyvalence rates	0.0004	

4. SIMULATIONS RESULTS

Dynamics

Figure 1 illustrates the global dynamics of the fishery, as it develops from an unharvested state, under open access conditions, for the case with both economic and biological differences between the two species. Total catches increase almost continuously over simulation time, while total effort displays three phases: (i) rapid increase; (ii) stagnation and slight decrease; and (iii) new increase and adjustment to open access equilibrium.

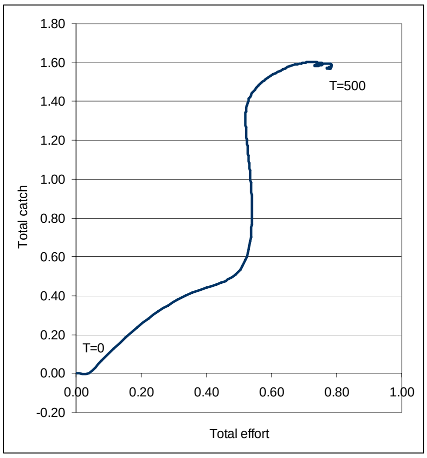

Figure 1. Evolution of total catch and effort with simulation time

This evolution results from the combined dynamics of effort and catches of the two species, as illustrated in figure 2.

Development of the fishery first occurs on species 2, which fetches higher prices, leading to a decrease in its productivity which entails both the development of exploitation of the least valued species, and a reduction of fishing effort in the fishery (as earnings per unit of effort become negative). Progressive development of effort on species 1 continues monotonously, while effort on species 2 displays progressively dampened oscillations, until the system adjusts to open access equilibrium.

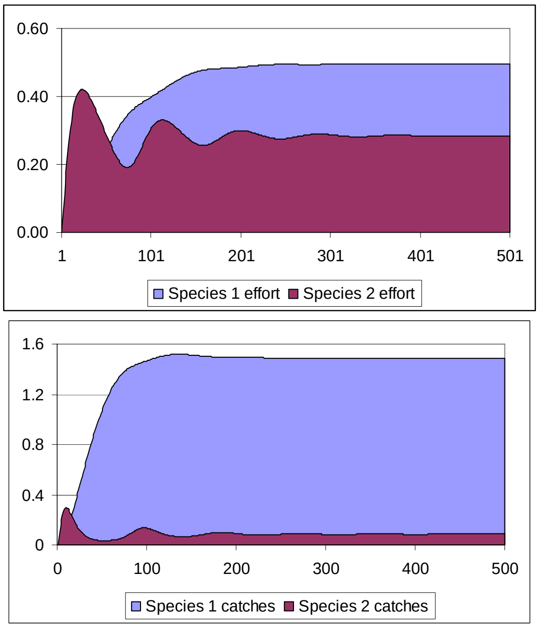

Figure 2. Evolution of effort and catches per species

Simulations for the case where the two species display similar biological characteristics but differences in prices lead to similar dynamics, only with increased oscillatory patterns for both species, effort and catches of the high-price species being much greater in this case.

4.1. Steady state equilibrium analysis

Results regarding steady state equilibria of the fishery are presented in terms of effort, biomass and rents.

As total effort increases in the fishery, its distribution between the two species is modified: while for low levels of effort, fishing concentrates on the high-price species (species 2), targeting of the low-price species (species 1) also develops at intermediate levels of effort (Figure 3).

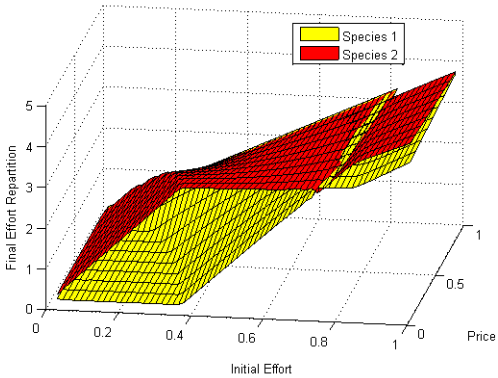

Figure 3. Equilibrium effort allocation per species, according to total effort level and price differences between species

The open access equilibrium status of the fishery varies according to the intensity of the price difference between the two species, and the total effort dedicated to the fishery. Two aspects can be highlighted here:

- The greater the price differences between the two species, the lower the equilibrium biomass for the same level of effort. This is due to the fact that a greater price difference entails a stronger concentration of fishing pressure on the high-price species, all else equal, hence a lower biomass of this species, particularly for intermediate levels of effort;

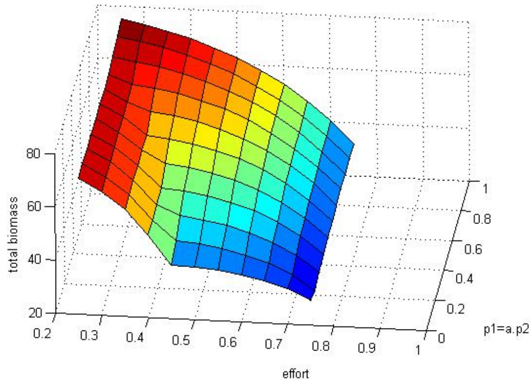

Figure 4. Equilibrium biomass according to level of total effort and price differences between species

- The decrease in equilibrium biomass of the system with increasing effort is sharper with increasing price differences, and displays a discontinuity. This results from the combination of different responses of the two species to differing harvesting pressure due to differing relative prices. As illustrated in Figure 5 below, with strong price differences and low levels of effort, the fishery mainly operates on the high price species (species 2), the biomass of which is thus reduced. Changes in total biomass thus reflect those observed for species 2. For intermediate levels of effort, the fishery partly operates on the low price species, hence its biomass is also reduced, while the equilibrium biomass of species 2 continues to decrease, although less rapidly. Changes in total biomass thus reflect the combination of changes in the biomass of the two species.

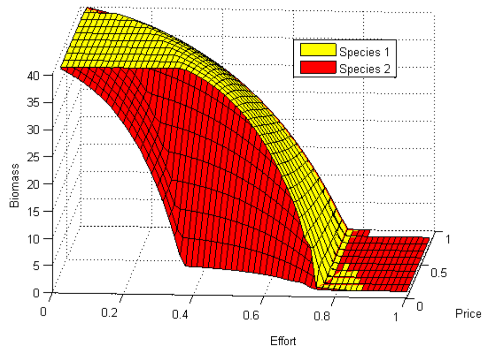

Figure 5. Equilibrium biomass per species for different levels of total effort and price differences between species

The equilibrium rents in the fishery for the different levels of effort and price differences are presented in Figure 6. High levels of rents can be achieved for intermediate levels of total effort if the prices of the two species are similar. Where price differences are important, however, maximum levels of rent will only be achieved if total effort is reduced. In this case, harvesting will be mainly on the high-price species.

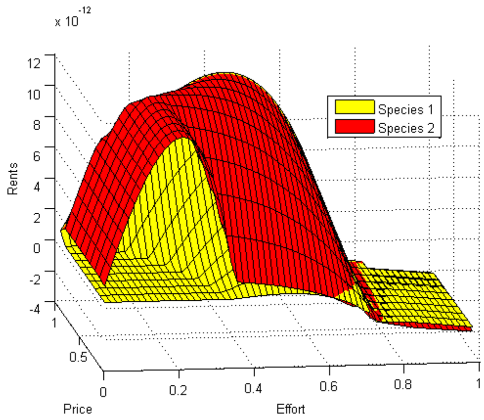

Figure 6. Equilibrium rents per species according to level of total effort and price differences

The existence of price differences between otherwise independent species harvested by the same fleets thus creates an interaction due to the possibility for effort to shift from one species to the other. This simple characteristic can lead to a sequential harvesting process, as described in the literature on trends in the composition of world fisheries landings, without including ecological response phenomena. For given levels of fishing effort, the existence of strong price differences between species will entail a concentration of this effort on the high price species, all else equal, leading to lower levels of biomass for this species as compared to situations where prices of the species are comparable.

5. CONCLUSION

In this paper, we develop a simple bio-economic model of an open access fishery targeting different species. We use a two species version of the model to analyse the consequences of price and biological differences between the two species on how the fishery may develop, from an unharvested state, and on the steady-state equilibria it may reach.

The model provides a simple illustration of the bio-economic drivers of a "fishing through the food web" process, i.e. without any ecological response mechanisms included in the analysis as would be implied by a "fishing down the food web process". Simulation results regarding steady state equilibria show that, where total effort is controlled but its allocation between alternative species may occur freely (a case of "regulated open access" which frequently occurs in contemporary fisheries worldwide), there may be significant consequences in terms of the biological status of stocks, and in terms of potential maximum rents. In effect, the re-allocation possibility creates an interaction between the two components of the fishery, which requires them to be considered jointly if one wishes to understand their dynamics and to identify possible management scenarios.

Further analysis based on the model will focus on the generalisation of these results in terms of the relative influence of key economic parameters on the dynamics and equilibria of the system, and in terms of the number of species included in the analysis.

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