Sustainability of a Fishery Under an Ecosystemic Constraint: A Stochastic Viable Control Model

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EXTENDED ABSTRACT

In this paper, we examine the biological and economic sustainability of a fishery subject to an ecosystemic constraint. We consider an age-structured discrete time dynamic model of two species of the Bay of Biscay (ICES area VIIIa,b), with uncertainty in recruitment: the European Hake and the Nephrops. These two species are exploited by the Nephrops fishery, mainly composed by trawlers. These trawlers target Nephrops and get juvenile Hakes as a bycatch, inducing ecological, technical and economical interactions.

We define sustainability using the viability framework of analysis. The viability objectives are represented by constraints and we examine what are the conditions on the bioeconomic states and exploitation decisions for the trajectories to respect that constraints. The viability of the fishery is depicted in terms of biological and economic constraints, and we define the probability that there are decisions ensuring the respect of the constraints despite the dynamic inertia and the uncertainties.

The economic constraint is defined as a minimal gross return for the fleet to be economically viable. In order to take into account the ecological impact of that fishery on the ecosystem, we also consider an ecological constraint defined as a minimal target threshold for the recruitment of mature hakes. As the main part of juvenile hakes catches in that area are due to the Nephrops fishery, this constraint can be respected only by a limitation on the fleet's fishing effort. We adopt an ecosystem approach for the Nephrops fishery management via the inclusion of a contraint on bycatch of another fish stock, the European Hake, in the analysis of the probabilistic viability of the fishery. This approach allows us to take into account ecosystem complexity, and interactions between species and human activities, without increasing the complexity of studied dynamic systems (especially the number of states, and the number of dynamic equations representing the bioeconomic system and their interactions).

Based on a stochastic analysis, we define the probability that both the economic and ecosystemic constraints are met, as a function of the level of these constraints. It means that we define the probability that a management policy allowing the dynamic exploitation system to respect both the economic and ecologial contraints exists. We compute this probability for any couple of economic and ecological constraint and show as a first result that the greater the sustainability objectives are, the lower the probability that there exist management decisions allowing to meet the constraint is.

We then examine the relationship between the economic and ecological constraints, and emphasize the necessary conflict between environmental and economic objectives in this model for a given probability level. The analysis uses a dynamic programming approach, with computation in Scilab.

INTRODUCTION

In the nowadays context of marine resources overexploitation, the sustainability of world-wide fisheries is highly compromised. The overcapacity of global fishing fleets leads to the capability of that fleets to alter considerably the size of both exploited fish populations and other species via ecosystemic effect. Present political objectives for fisheries management include stopping overfishing, rebuilding overfished stocks, minimizing bycatch and protecting essential fishs habitats. The European Commission and the FAO emphasize the importance of an ecosytem-based framework for fisheries management (Garcia et al., 2003). The purpose of such integrated approaches is to provide sustainable management tools that take into account biological, social and economic objectives at the same time. Unfortunately, despite political declarations, developping an operational framework for an ecosystem-based approach to fisheries management is technically difficult, as it requires to take into account several dynamics (biological and economic and social), their interactions, and the uncertainty inherent to the considered biological and social patterns. Nevertheless, an important issue is to take into account ecosystem complexity, and interactions between species and human activities, without increasing the complexity of studied dynamic systems (Charles, 2005). One way to escape from the ecosystemic complexity is to extend the use of single species performance measures and references points (ICES, 2003a,b) by taking into account specific interactions with nontarget species (Hall and Mainprize, 2004).

The Bay of Biscay (ICES fihing areas VIIIa and VIIIb) hake-nephrops mixed fishery has a major economic importance both at the regional and national scale. The Bay of Biscay hosts one of the most important nurseries of the Northern stock of hake (ICES, 2003a). In recent years, estimated fishing mortality of hake was just above the fishing mortality corresponding to the precautionary approach and the hake Spawning Stock Biomass (SSB) as declined until it stabilized to a low level in the early 90's, raising serious doubts about the fishery's sustainability. A recovery plan was enforced in 2004. At the same time, hake consitutes an important by-catch in the Bay of Biscay nephrops fishery. Nephrops fisheries induce at least half of the fishing mortality of the three first age groups of hake (immatures). A recovery program on hake population must then take into account the nephrops fisheries activity. According to Drouineau et al. (2006), it is urgent to find new regulation measures in order to achieve sustainability of this mixed fishery. An important issue is thus to examine the possibility to define a viable exploitation of the Bay of Biscay Nephrops while limiting the by-catch impact on the Hake population.

In this paper, we propose a viability analysis of the hake-nephrops fisheries issues. We examine how to conciliate economic objectives for the nephrops fishery while taking into account ecological impact of its fishing activity on the hake population. We develop a discrete time dynamic per recruit model with uncertainty in recruitment. We use the recruitment of mature hakes as an indicator of ecosytemic impact of the nephrops fishery. This is a proxy indicator of the regeneration of the stock.

Using the viability approach in a stochastic framework, we examine the probability that sustainability goals are achieved over a finite time horizon. It makes it possible to analyse the trade-off between sustainability goals in natural resources management issues, when environmental uncertainty occurs. This framework is then applied to the more specific case of technical interaction consequences in fisheries management. For this puprose, we develop a viability analysis of the nephrops fishery under an ecosytemic constraint represented by a limitation of the bycatch level in order to allow a stock recruitment. Sustainability objectives are defined such that a minimal gross return is guaranteed to the Nephrops fishery while the Hake stock is kept into biological limits making the reproduction of the species possible. To represent this ecological objective, we define a constraint on the mature recruitement, ensuring a minimal Spawning Stock Biomass.

In a stochastic framework, the viability is defined as the probability that viability constraints are satisfied at any time, given the environmental uncertainty on recruitement and the dynamic inertia. We compute the viability probability for a range of ecological and economic constraints levels. The purpose is to exhibit trade-offs in sustainability objectives represented by the constraints levels.

The paper is organized as follows. First, we present the discrete time model representing the population and economic dynamics. We define the sustainability objectives, and describe the viability approach. Then, numerical estimates of the sustainability probabilities are presented. Finally, we provide concluding remarks.

MODEL

To represent the ecological and economic interaction in the ecosystem, we model the biological dynamics of two species, the european hake (*merlucius merlucis*) and the nephrops (*nephrops norvegicus*). We represent the dynamics of the two species with an age-structured model inspired by the classical representation proposed by Gulland (1965). As there are no biological interactions between the Nephrops and Hake species, we use two Single-Stock models. We can refer to the recent survey of xiao (2007) for the mathematical description of such models for fisheries management (Virtual Population Analysis models that reprensent an estimation of the age strucutre of a stock). The age-groups are represented by $a=1,\ldots,A$, where A is the “plus-group” composed by individuals of A years and more.

The abundance of each species is defined by a number of individuals of age groups $a=1,...,A$. We denote N_t^s the abundance vector of species s at year t, where $s=h,n$, respectively for hakes and nephrops (and thus $N_t^s(a)$ is the abundance of the a-group). The dynamics of the resource is described by

$$N_{t+1}^s = f(N_t^s, u_t, \omega_t) \quad (1)$$

where u_t, the control variable, is the fishing effort multiplier that defines the fishing mortality F_t^s, i.e. the impact of the fishing effort and catches on the stock dynamics, and ω_t is the stochastic parameter representing the environmental uncertainty on recruitment.

The first group, denoted group 1, is composed by the new recruits. The number of recruits may depend on many factors, including the size of the genitor stock and some environmental factors. It leads to uncertainty on the recruitement. To represent the uncertainty, we define the recruitement functions, depending on an uncertainty parameter ω_t. For this study, as there are no established stock-recruitment relationship for the two sudied species, we consider the following uncertain recruitment relationship

$$N_{t+1}^s(1) = \omega_t^s \quad (2)$$

where ω_t^s follows a Normal distribution with mean recruitement $\overline{N_0^s}$ and standard deviation σ^2. Parameter of the Normal distributions have been defined such to minimize the least square error between observed and predicted recruitments.

For other age groups *(a=1,...,A-2),* the number of individuals of age *a+1* at year *t+1* depends on the number of individuals of age *a* at year t that survied. We distinguish

- the natural mortality rate $M^s(a)$,
- the fishing mortality $F_t^s(a)$.

The dynamics read

$$N_{t+1}^s(a+1) = N_t^s(a)(1 - M^s(a) - F_t^s(a)).$$

The last group *A* is a "plus-group" that includes all fishes older than *A*. Its dynamics reads

$$N_{t+1}^s(A) = N_t^s(A)(1 - M^s(A) - F_t^s(A)) + N_t^s(A-1)(1 - M^s(A-1) - F_t^s(A-1))$$

The fishing mortality is due to fishing effort and is related to an economic activity. The nephrops fishery is targeting nephrops but gets hakes as a bycatch. It thus induces a fishing mortality $F_t^n(a)$ and a fishing mortality $F_t^h(a)$. Nevertheless, hakes are also captured by other fleets, leading to an additional fishing mortality $F_{\#}^h$, that we consider constant in the present analysis: As we are interested in the mortality of the first age groups of hakes (youth) and given that the fishing mortality on that groups is mainly due to the nephrops fishery, we do not consider changes in the fishing effort of hake fisheries. In this paper, we only consider the nephrops fishing activity, and the fishing mortality of hakes due to other fleets will be considered constant through time for all age groups.

The fishing mortalities at year t depend on the fishing effort of the fleet targeting nephrops. This effort is defined with respect to a reference fishing mortality F_{ref}^s, and an effort multiplier u_t

$$F_t^n = u_t F_{ref}^n \quad (3)$$

$$F_t^h = u_t F_{ref}^h + F_{\#}^h \quad (4)$$

We are interested in the catches of the nephrops fishery: the nephrops catches that generate the gross return of the fleet, and the juvenile hakes catches that induce ecological and economic looses. The catches $C_t^s(a)$ of the a age group of species s at year t are defined by

$$C_t^s(a) = N_t^s(a) F_t^s(a) \quad (5)$$

The gross return of the nephrops fishery at year t is defined as a linear function of the catches (the profit function G depends on the discard rate, the weight at age, and the prices, that are all considered constant parameters).

$$\pi_t = G(C_t^n) \quad (6)$$

Data

Biologic data for the nephrops stocks come from ICES (2003b). For the hake population dynamics and the mortality rates of the nephrops fishery on hakes, we refer to ICES (2003a).

Sustainability Objectives

We define the sustainability of the fishery by taking into account economic objectives and the ecological impact of the Nephrops fishery on the hake population. Sustainability is thus defined as the satisfaction of economic and ecological constraints in a dynamic way.

On the one hand, we consider that the Nephrops fishery is economically viable if the gross return is greater than a threshold π_{min}. This minimal threshold is the economic objective for sustainability. On the other hand, we consider that the fishery is ecologically viable if its impact on the Hake biology is compatible with sufficient recruitment of mature hakes. For this purpose, we define a targeted recruitment of the fourth age group of hakes N^h_{min}. As the mortality of juveniles is mainly due to the nephrops fishery, a constraint on the hake mature recruitement will limit the nephrops fishing activity. The fourth hake age group is the first group to contain mature individuals. The ogive of sexual maturity for hake is

Age group	1	2	3	4	5	6	7+
% of mature individuals	0	0	0	0.2	0.6	0.9	1

This ecological constraint insures that there is a minimal number of mature individuals (genitors) in the stock population. It can be interpreted as a minimal contribution of the age-group 4 to the Spawning Stock Biomass.

To be sustainable, the Nephrops fishery must then satisfy the following conditions at all year *t*

$$\pi_t \geq \pi_{min} \quad (7)$$

$$N^h(4) \geq N^h_{min} \quad (8)$$

METHOD

To characterize the sustainability of the fishery, we use the viability approach (Aubin, 1991). This framework allows to study the consistency between intertemporal trajectories and contraints in dynamic systems. It has been applied to the sustainability issue in Martinet and Doyen (2007), and to the study of fisheries sutainability and recovery processes in Martinet et al. (2007).

An intertemporal path is viable if it respects all of the constraints at all time period, i.e. dynamically and not only at the present time. It means that some bioeconomic states may allow to satisfy the sustainability constraints in the short term, but without allowing the system to satisfy these constraints in the long run, given the dynamics of the system and the related inertia.

We introduce the characteristic function

$$\mathbb{I}(N^s_t, u_t) = \begin{cases} 0 & \text{if constraints (7-8) are satisfied} \\ 1 & \text{otherwise} \end{cases}$$

that is an indicator of the satisfaction of the viability constraints.

In our analysis, we examine what sustainability goals (i.e. viability constraints) can be achieved from the initial configuration of the system. As we consider uncertainty in the model, we examine the probability that, from the initial state, there are intertemporal decisions controls $u(.)$ that satisfy the constraints, i.e. the probability that there are viable trajectories starting from the initial state, given the uncertainty on recruitment. For that purpose, we consider the objective function

$$\mathcal{J}(\pi_{min}, N^h_{min}) = \inf_{u(.)} \sum_{t=t_0}^{t_0+T} \mathbb{I}(N^s_t, u_t)$$

and examine, for a range of constraint levels, if there are decisions such that this objective function is nil (all the contraints are respected over the considered horizon).

We thus examine the viability of (possible) trajectories starting from a given initial state taken as a reference point. This state is the bioeconomic configuration of the fishery at the reference year, i.e. in 2003. Moreover, to run the analyse, we consider a finite time horizon. An exploitation trajectory is viable on a horizon *T* if both the economic constraint (7) and the ecological constraint (8) are satisfied for all $t=t_0,...,t_0+T$. We examine the probability that viable exploitation decisions exist, i.e. that there are some intertemporal fishing effort that make it possible to satisfy the sustainability objectives.

For any pair of sustainability objectives (π_{min}, N^h_{min}), we define the probability that there are exploitation decisions, i.e. intertemporal fishing efforts, that make it possible to match with the sustainability objectives.

$$\mathcal{P}(\pi_{\min}, N^h_{\min}) = \mathbb{P}_\omega \left(\forall t = t_0, \ldots, t_0 + T, \; \exists\, u_t \left| \begin{array}{l} N^s_{t+1} = f(N^s_t, u_t, \omega) \\ \pi_t \geq \pi_{\min} \\ N^h(4) \geq N^h_{\min} \end{array} \right. \right).$$

We compute for all combination of constraints level, i.e. of economic and ecological viability objectives, the probability that viable decisions and intertemporal paths exist. This analysis requires to define if there exist intertemporal fishing decisions that make it possible to satisfy the constraints along time, given the uncertainty ω on recruitment.

Instead of analysing all possible intertemporal trajectories (N^h_t, N^s_t) starting from the initial biological state $(N^h_{t_0}, N^n_{t_0})$, and associated intertemporal fishing effort *u(.)*, we use the fact that the greater the fishing effort, the greater the annual gross return, and the lower the remaining fish stock. We determine a limit harvesting strategy u^* such that if this fishing strategy makes it possible to respect the constraints over the time horizon there are (obviously) viable strategies, and if this strategy leads to an exploitation trajectory that does not respect the constraint, there are no viable exploitation strategies.

Definition : *We define the minimal profitable effort that is the minimal effort to be consistent with the gross return target* π_{min} as follows

$$u_t^* = min \langle u | \pi_t \geq \pi_{min} \rangle$$

If the fishing mortality multiplier is greater that u_t*, the gross return will be higher than the economic viability level π_{min}. On the contrary, if u_t is lower than the minimal profitable effort, the economic constraint (7) will be violated.

We propose a numerical computation using Scilab environment. The algorithm of computation consists in running a great number of uncertain recruitment scenarios, with optimal decisions sequences u_t*. We then define the ratio of the viable trajectories, for which the objective function is nil, over the total number of scenarios.

To define the viability probability associated with various constraints level, we make a loop of the computation algorithm on a discretization of the constraint map $[\pi^{low}_{min}; \pi^{high}_{min}] \times [N^{low}_{min}; N^{high}_{min}]$. The computation duration depends on the precision of the discretization. For each constraint level, we run numerous simulations with random recruitment (we analyse the viability of the trajectories for 10000 recruitment scenarii) and analyse if the minimal harvesting strategy satisfying the economic constraint (7), i.e. $u*_t$, also satisfies the ecological constraint (8).

RESULTS

The results are represented on Figure 1

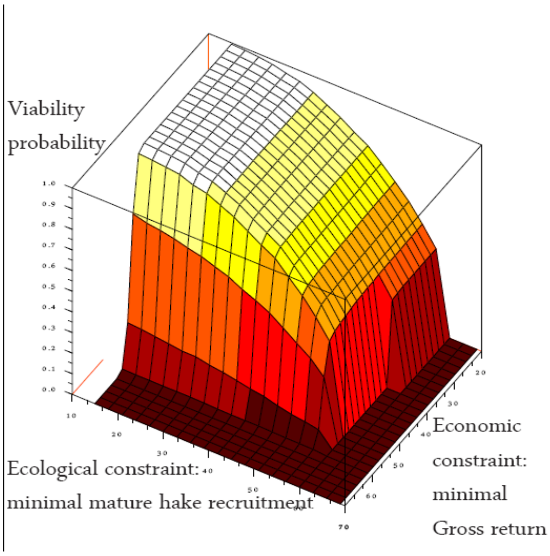

Figure1: *Viability probability with respect to the gross return and bycatch constraints levels.*

We see on Figure 1 that the probability to have a viable exploitation decreases with both the constraints levels π_{min} and N^h_{min}. The greater the constraints are, the lower the probability that they are respected is.

Such an analysis makes it possible to define a set of management objectives with an associated risk (probability of success). One can thus define the set of possible sustainability objectives S_β that can be achieved with probability level greater than β. For example, the set of sustainability management objectives that can be achieved with a probability greater than β=0.9 is defined on Figure 2

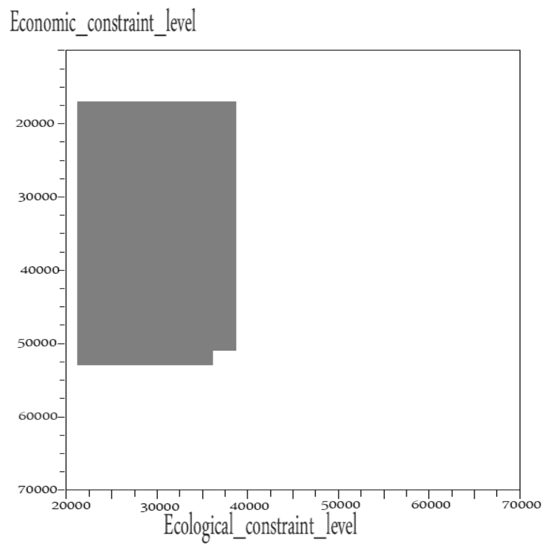

Figure 2: *Set of sustainability objectives that can be achieved with a probability β=0.9.*

Let us consider particular values of the constraint levels π_{min} and N^h_{min}. We provide illustrative trajectories starting from the initial biological state of the fishery, and characterized by the optimal fishing effort u_t* (and thus by a constant guaranteed gross return).

Figure 3 presents the recruitment of mature hakes associated with five recruitment scenarii.

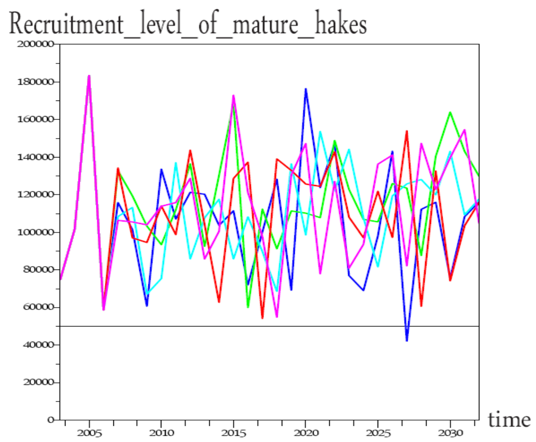

Figure 3: *Mature hakes recruitment level for simulated trajectories.*

The minimal fishing effort multiplier associated with the gross return constraint for the associated trajectories is given in Figure 4.

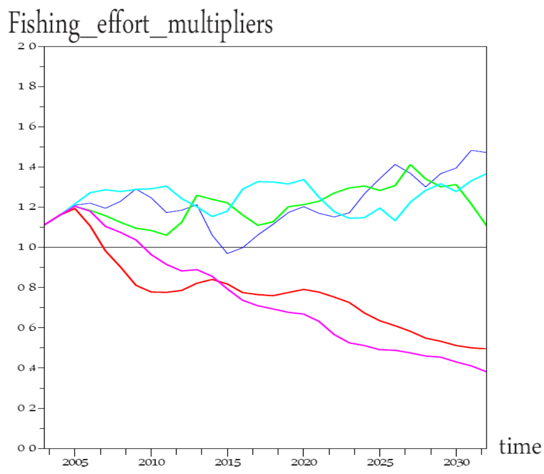

Figure 4: *Optimal fishing effort multipliers*

From a general point of view, considering the economic and ecological sustainability targets at the reference year (2003), which are respectively $\pi_{min} = 55000\,keuros$ and $N^h_{min} = 45000$, one can see that the viability probability associated with these constraint level is low. Economic and ecological requirements are thus lowly compatible in the present technical configuration of the exploitation.

CONCLUSION

In this paper, we proposed a framework based on the viability theory to discuss the trade-off between sustainablity objectives in fisheries management with environmental uncertainties. We developped a two-stock age stuctured population model with uncertain recruitement, and an economic model of a fishery exploiting the stocks. We describe the viability of the fishery thanks to an economic objective (minimal gross return) and take into account its impact on the ecosystem thanks to a constraint on the minimal recruitment of mature individuals of an endangerous species.

We examine the probability that both the economic constraint and the ecosystemic constraint are satisfied over the considered time horizon.

Our approach makes it possible to define the set of sustainability goals that are reachable with a given probablity of success.

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