RECOVERING SUSTAINABLE FISHERIES

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ABSTRACT

In this paper, we study recovering processes for fisheries facing crisis or over-exploitation of a marine renewable resource. We examine how to restore resource stocks and modify the economic characteristics of the fleet in order to put on a sustainable exploitation system, near of some maximal standard as the Maximum Sustainable Yield. We define the sustainability of the exploitation with respect to both economic and biological constraints. Biological constraints are bases on the definition of a minimal resource stock to be preserved in order to insure the resource regeneration. Economic constraints include a minimal size for the fleet (number of vessels, which induces a social constraint on the employment) and a minimal profit per boat. We use the viability framework to consider the favorable situations of the bio-economic system in which a sustainable exploitation is possible, i.e. viable states that make it possible to satisfy the co-viability conditions in the long run, taking into account dynamical properties of the system. Along with the definition of such favorable states, we examine transition phases to reach sustainable configurations from a crisis situation. We characterize the recovering paths studying the economic cost of limiting catches during recovery period, and the length of this transition period. The developed framework makes it possible to study the sensitivity of the various constraints on that cost and time, and to minimize either one or the other. To avoid recurrence of the over-exploitation problems, we characterize sustainable decisions associated with viable states, for the dynamical evolution of the system. It includes decisions on the effort allocated to each vessel, and decisions on the modification of the size of the fleet. We develop a global model for a single resource stock. As an illustration, we study the recovering of the Nephrops stocks in the Bay of Biscay, taking into account both conceptual and applied issues. <P>

Keywords: sustainable fishing, recovery, fishery policies, bio-economic modeling

INTRODUCTION

According to recent studies, the maximum production potential of marine fisheries worldwide was reached at least two decades ago; since then, due to the widespread development of excess harvesting capacity, there has been an increase in the proportion of marine fish stocks which are exploited beyond levels at which they can produce their maximum (Garcia and Grainger, 2005; FAO, 2004). Hence, the problem of managing fisheries is increasingly cast in terms of restoring them to both higher and sustainable levels of fish stocks, catches, and revenues from fishing. Examples are the restoration plans discussed and/or adopted by the European Commission in recent years for several collapsed stocks in E.U. waters, or the international commitment to return fisheries to levels allowing their maximum sustainable yield to be extracted by 2015, taken by countries present at the Johannesburg Summit on Sustainable Development in 2002.

The problems posed by fisheries restoration are dynamic in nature: beyond the issue of selecting adequate objective levels for restored fisheries, a key question is the identification and the selection of the possible paths towards these objective levels. In practical situations, this question is crucial as it relates to the feasibility (technical, economic, biological) and to the social and political acceptability of the adjustments required for fisheries to be restored, hence to the actual possibilities to drive fisheries back towards decided sustainability objectives.

The definition of optimal strategies for the harvesting of marine fish stocks has been widely studied in the literature on renewable resource management. While most of the initial work focused on the comparative statics of the problem, analysis of the dynamics of bio-economic systems has developed as a substantial body of literature. Different approaches have been proposed. In the domain of fisheries, Clark (1985) described how to optimally drive a dynamic bioeconomic system towards a stationary state, based on a single command variable (fishing effort), and looking at a single optimization criteria (net present value of the expected benefits derived from harvesting). Alternative approaches have been based on simulations of specific adjustment trajectories for given bioeconomic systems, according to predetermined scenarii, and on their *a posteriori* evaluation with respect to various criteria (see e.g. Smith, 1969; Mardle and Pascoe, 2002; Holland and Schnier, 2006).

In this paper, we develop a formal analysis of the recovery paths for a fishery, based on viable control theory. This allows us to characterize of the dynamics of a fishery in terms of its capacity to remain within pre-defined constraints, beyond which its continued long-term existence would be jeopardized. The constraints considered in the analysis relate to micro-economic, biological and social factors. Following Béné et al. (2001), we use the mathematical concept of viability kernel to identify the set of states of the fishery for which it is possible to satisfy these constraints dynamically. This kernel represents the ``target'' states for a perennial fishery. Our analysis focuses on the ways by which the fishery can recover from states outside the kernel to viable states in general, and to specific target states in particular. We use the concept of minimal time of crisis Doyen and St-Pierre (1997) to consider the horizon at which such targets can be reached, and examine transition paths considering transition time and transition costs defined as the discounted sum of fleet profits during the transition phase toward target states.

The analysis is applied to the case of the bay of Biscay (ICES area VIII) Nephrops fishery, and focuses on the implications of restoring this fishery to levels allowing maximum sustainable yield to be extracted. We examine the relationship between the viability of the fishery on the one hand, and the possible transition phases towards this maximum yield objective on the other hand.

The paper is organized as follows. The simplified model of the bay of Biscay Nephrops fishery used for the analysis is presented, as well as the definition of the economic, biological and social constraints determining the viability of the fishery. We then present the analysis of the conditions under which these constraints can be satisfied throughout time, and of the possible transition paths towards these viable states from initially non-viable situations. The specific issue of recovering MSY production levels without jeopardizing the viability of the fishery is analyzed.

DEFINING A SUSTAINABLE FISHERY

A bio-economic model of the fishery

In this paper, we consider a single stock fishery, characterized by the size of the fleet X_t which can evolve in time. The exploited resource is represented by its stock S_t with the carrying capacity of the ecosystem K.

We use a discreet time version of the ``logistic model'' of Schaefer (1954) to represent the fish stock's renewal function. Hence, the regeneration of the resource stock is given by

$$R_t(S_t) = rS_t\left(1 - \frac{S_t}{K}\right). \qquad (1)$$

The fleet is assumed homogenous. Each vessel has the same access to the resource and the same harvesting characteristics. Global catches are defined by

$$C_t = qS_te_tX_t \qquad (2)$$

where q represents the catchability of the resource. Following Gordon (1954), the dynamics of the resource reads

$$S_{t+1} = S_t + R_t - C_t = S_t + rS_t\left(1 - \frac{S_t}{K}\right) - qS_te_tX_t \qquad (3)$$

The economic dynamics are characterized by the per vessel profit. This profit depends on the landings L_t of the resource defined with respect to the per vessel catches $c_t=C_t/X_t=q\ S_t\ e_t$ and a discard rate τ_d.

$$L_t = (1-\tau_d)qS_te_t. \qquad (4)$$

These landings give the gross return for the targeted species which is a part λ of the vessel's total gross return. Vessel profit thus reads

$$\pi_t = \Big(p(1-\tau_d)qS_te_t\Big)\frac{1}{\lambda} - (\beta_1 + \beta_2 e_t) \qquad (5)$$

where p is an exogenous resource price that is considered constant. β_1 represents fixed costs and β_2 a per effort unit cost.

We consider that the production structure is (slowly) flexible, in terms of both capital and labor. The size of the fleet evolves according to a decision control ξ_t,

$$X_{t+1} = X_t + \xi_t. \qquad (6)$$

To take into account the inertia of capital, the change of the fleet size is limited. A maximum number α_2 of vessels can enter the fishery in any time period, due to technical constraints. The number of vessels exiting the fleet in any time period can not exceed α_1, due to social and political constraints (see below).

$$-\alpha_1 \leq \xi_t \leq \alpha_2. \qquad (7)$$

This means that level of capital in the fishery (number of vessels) cannot change quickly. On the other hand, fleet activity (effort per period e_t) can change, and even be set to nil. The dynamics of the bio-economic system is thus controlled by the effort $0 \leq e_t \leq \bar{e}$ (day of sea per period and per vessel and the change in the fleet size $\alpha_1 \leq \xi_t \leq \alpha_2$, the number of boats entering or exiting the fleet.

Sustainable exploitation patterns

We define sustainability of the exploitation with respect to a set of biological, economic and social constraints that have to be respected throughout time for a viable fishery to exist.

Biological constraints: In order to preserve the natural renewable resource, we consider a minimal resource stock S_{min} which is the minimal biomass ensuring the regeneration of the stock:

$$S_t \geq S_{min} \qquad (8)$$

Economic constraints: We consider an individual economic constraint on the vessel performance: profit per vessel is required to be greater than a threshold π_{min} for economic units to be viable.

$$\pi_t \geq \pi_{min} \qquad (9)$$

This minimal profit is defined such as to ensure remuneration of both capital and labour, at least at their opportunity costs. It can also be set as a sustainability goal ensuring level of economic performance greater than those ensuring strict economic viability.

Social constraints: To take into account social concerns, the viability of the fishery is described by a constraint on the fleet size. We require the number of vessels to be greater than a threshold X_{min}:

$$X_t \geq X_{min} \qquad (10)$$

ensuring a minimal employment and activity in the fishery.

In addition to this minimum fleet size, we assume that the speed at which fleet size can be reduced is also limited. The constraint on the adjustment possibilities regarding the fleet size can be interpreted as a social and political constraint limiting the number of vessels (and employment) leaving the fleet.[1]

Considering the state constraints (8) and (9), viability requires as a necessary condition on the bioeconomic configurations. Nevertheless, it does not mean that this whole state constraint set make it possible to satisfy the profitability constraint. In particular, the biological configuration for which it is possible to have a profitable fishing activity can be determined. It appears that the profit constraint (9) induces stronger limitations on stock size than the biological constraint (8):

$$\underline{S} = \frac{\pi_{min} + (\beta_1 + \beta_2 \bar{e})}{pq\bar{e}}. \qquad (11)$$

This induced constraint comes from the fact that a minimal effort is required to satisfy the profitability constraint (9). This minimal effort depends on the resource stock as the catches increase with the resource stock:

$$\underline{e}(S_t) = \frac{\pi_{min} + \beta_1}{\frac{p}{\lambda}(1 - \tau_d)qS_t - \beta_2} \qquad (12)$$

This minimum effort is represented with respect to the resource stock in Fig.1. The vertical asymptote represents the stock for which fishing effort has a nil marginal value. The fishing effort required to satisfy the profit constraint is a decreasing function of the stock size. The more fishes there are, the less fishing effort to catch them is needed. The horizontal line represents the maximal days of sea per period. One can see that there is a stock threshold $\underline{S}$ for which the number of days required to satisfy the profit constraint is greater than the possible number of days per period.

[1] This interpretation is somewhat different from that encountered in the literature regarding capital inertia, which is assumed to result mainly from the lack of possibilities to quickly reallocate specific fishing assets to alternative uses, a technical, rather than social constraint.

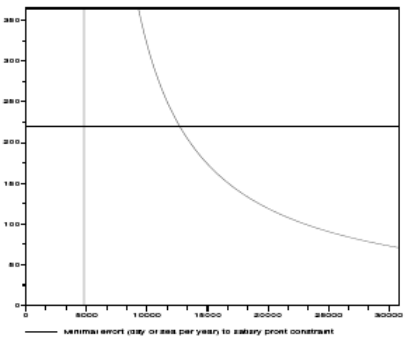

Fig. 1. Minimal effort $\underline{e}(S_t)$ required to satisfy profit constraint (9), with respect to the stock size.

We thus have an induced constraint for the fishing activity to generate sufficient profits. This constraint level is greater than the initial resource constraint S_{min}, which means that ensuring the economic profitability of the fishery in the long run implies that the resource constraint is also satisfied. This result was also derived by Béné et al. (2001).

Model parameters:

The analysis is applied to a case study: the Bay of Biscay Nephrops fishery (ICES area VIII). Biological parameters are estimated using CPUE series (catches per unit of effort) as an index of abundance. We used nonlinear parameter estimation techniques to find the best fit of the predicted biomass, given the observed catches. The fitting criterion is the minimization of the squared deviation between observed and predicted CPUE (see Hilborn and Walters, 1992), adjusted for changes in effort and fishing efficiency of vessels. Economic parameters are estimated using costs and earnings data collected by the Fisheries Information System of Ifremer via surveys of individual vessel owners.

Estimated parameters values, and constraint levels are given in the following table.

Parameter	value	Constraint	level
$r =$	0.78	$S_{min} =$	5,000 tons
$K =$	30800 tons	$X_{min} =$	100 vessels
$q =$	72.10^{-7} j^{-1}	$\pi_{min} =$	130,000 euros
$p =$	8,500 euros per tons	$\alpha_1 =$	10
$\beta_1 =$	70,000 euros per year	$\alpha_2 =$	10
$\beta_2 =$	377 euros per day of sea		
$\bar{X} =$	500 boats		
$\bar{e} =$	220 days		
$\tau_d =$	33%		
$\lambda =$	43%		

In 2003, the fleet was composed by 235 vessels, of an average profit of 165 000 euros. The resource stock was about 18 600 tons. The average number of days of sea was 203. The catches were about 5769 tons.

DYNAMIC ANALYSIS OF THE FISHERY

In this section, we examine the consistency between the dynamics of the exploited system and the viability constraints, focusing on conditions for fishing activity to be viable in the long run.

Open access *vs*. optimal harvesting strategies

Following Clark (1990), the dynamics of the system can be compared under two exploitation patterns: open access, and a policy guided exploitation maximizing the intertemporal profit derived from the fishery, which we call Cost-

Benefit Analysis (CBA). We analyze the possible dynamics of the fishery under these two scenarios. Fig. 2 represents the intertemporal dynamics of resource stock, fleet size and per vessel profit for the two exploitation patterns on a 50 years period. We compute 16 intertemporal paths representing various representative initial states.

Open Access: The open access case corresponds to situations in which vessels can freely enter and exit the fishery, subject to the inertia constraints described above, and choose their individual effort level. In that case, the individual effort will be maximal, as the marginal productivity of effort is positive when the stock is large enough.

We consider that, if individual profit is greater than the minimal profit π_{min}, the fleet size increases as new vessels enter the fishery. On the contrary, if profits are less than 90% of the π_{min} level, vessels leave the fleet. This represents the fact that negative profits often occur transitionally in fisheries: some negative profits may be supported for short periods.

It appears that in this open access case, whatever the initial stock configuration, the system reaches a limit cycle in both the resource stock and the fleet size.[2] In the case considered, the stationary state is characterized by 263 vessels and a resource stock of 14 400 tons. The individual profit at this stationary state is minimal (π_{min}).

Cost-Benefit Analysis: Considering that the fishing fleet is regulated in order to maximize profit derived from the fishery, it is possible to establish the sets of optimal decisions concerning effort levels and changes in fleet size, for different initial conditions in the fishery.

At fleet level, the optimal behavior is determined by maximizing the intertemporal sum of discounted fleet profits, with respect to the allocation of the fishing effort through time, which reads

$$\max_{e(.)} \sum_{t=t_0}^{\infty} \frac{1}{1+\delta(t-t_0)} X_t \Big(pqS_t e_t - (\beta_1 + \beta_2 e_t) \Big) \qquad (13)$$

where δ represents the social discount rate or, from a microeconomic perspective, the opportunity cost of capital. In the general framework, the optimal solution of such a problem (Clark, 1990) is to reach an optimal steady state following a ``bang-bang" strategy (or most rapid approach). In our model, we can see that, whatever the initial state, the system reaches such a stationary state, with a high stock level and a lower fleet size, making it possible to maximize the catches while minimizing harvesting costs. The stationary state is reached as quickly as possible. In the case considered, this stationary state is characterized by 190 vessels and a resource stock of 19 000 tons. The individual profit is greater than the minimum viability profit π_{min}. It is of 222 000 euros per vessel.

Nevertheless, there is no ``bang-bang" strategy as there is an inertia in the capital (fleet size) adjustment. When the fleet size is smaller than the targeted size, the stock size and the profit level evolve smoothly, with increasing or decreasing profit, depending on the resource stock (the larger the stock, the more harvesting and profit). On the contrary, when the fleet size is large and require a long time period for adjustment, we observe an alternance of nil harvesting and maximal one. The larger the fleet, the larger the variations of profit and stock size during the transition phase.[3]

In both exploitation scenarii, a minimum profit is guaranteed after a transition phase. When a steady state is achieved, both the minimum profit per vessel and the resource stock are lower in the open access case then in the regulated case, while the fleet in the open access regime is larger. Open access profit is characterized by periodical oscillations around the profitability constraint, ensuring a minimum profit lower than the economic viability constraint.

The time of transition can be long: it is between 10 to 25 years in the open access configuration, and between 3 to 25 years in the regulated case. During this transition phase there is no guaranteed profit for the fleet.

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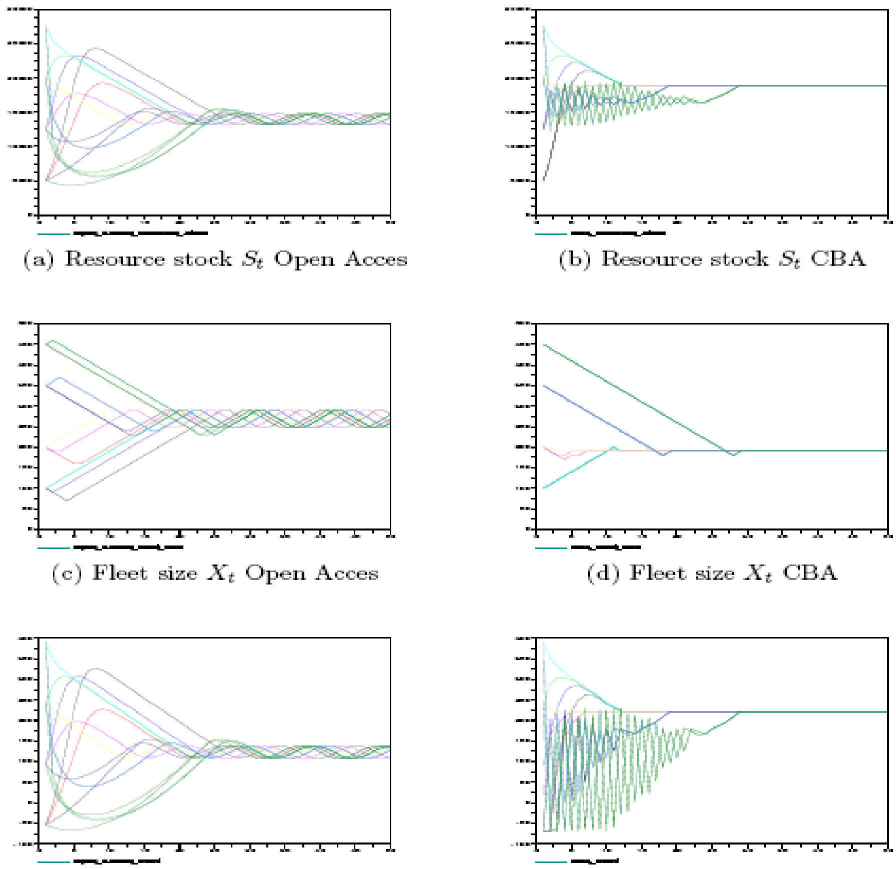
[2] The periodic behavior observed here is linked to the choice of the adjustment possibilities in vessel numbers. We consider that, in a free access configuration, a maximal number of vessels will enter the fishery if there are some positive profits. A finer adjustment parameter (a slower entry) would lead to smaller variations. The extreme case of a continuous capital stock adjustment would lead to a steady state point. Note that the resource can not be exhausted as, when the stock is reduced to low levels, the catches per unit of effort become very small, and the marginal profit of effort is negative.

[3] The observed amplitude of variations does not depend on the size of the resource stock, just on that of the fleet.

The two harvesting scenarios considered here thus lead to paths that do not respect the viability constraints, as defined in the previous section, at least until the transition phase is achieved (and periodically for the open access strategy from then on). If these constraints apply, it is possible that some of the trajectories represented above may actually lead to situations of crisis due to a collapse of the stock, the economic extinction of the fishery, or to social unrest associated with the adjustment paths considered. We propose to analyze the viability of the fishery by defining intertemporal paths of harvesting that satisfy all the constraints defined in the previous section simultaneously.



(a) Resource stock S_t Open Acces (b) Resource stock S_t CBA

(c) Fleet size X_t Open Acces (d) Fleet size X_t CBA

(e) Profit π_t Open Acces (f) Profit π_t CBA

Fig. 2. Initial conditions are combining four stock levels (5 000, 12 500, 20 000 and 27 500 tons) and four fleet size (100, 200, 350 and 450 vessels).

Viable harvesting strategies

The aim of this section is to define state configurations (resource stock and fleet size) which are compatible with our viability constraints. The question is to determine whether the dynamics (eq.3 and 6) is compatible with the set of constraints. For this purpose, we use the viable control approach and study the consistence between dynamics (3) and (6) and the constraints (7), (8), (9) and (10).

Viable stationary states: A first analysis relies on the definition of viable stationary states. These states are characterized by $S_{t+1}=S_t$ and $X_{t+1}=X_t$. We thus have $\xi_t=0$ and

$$R_t = C_t \quad \Leftrightarrow \quad e_t X_t = \frac{r}{q}\left(1 - \frac{S_t}{K}\right)$$

We can determine admissible pairs (X_{SS}, e_{SS}) with respect to resource stock S. Extreme cases correspond to maximal effort $\bar{e}$ on the one hand (which leads to a linear relationship between the fleet size and the resource stock), and minimum effort $\underline{e}(S_t)$ on the other hand. These two frontiers are represented on Fig. 3. The inner area corresponds to possible stationary states that satisfy all the constraints, including the profitability constraint.

We can see on Fig. 3 that there is a maximal sustainable size for the fleet, when the effort is minimal. It is interesting to note that the stock level associated with the maximal sustainable size of the fleet is not equal to the stock producing the MSY. This is due to the fact that a greater stock produces fewer yields but ensures less costly catches.

In our illustrative case, the maximum sustained fleet size is 279 vessels. It is associated with a resource stock of 17,600 tons and a per vessel effort of 166 days of sea.

<u>Viable states</u>: In our problem, there are some states that do not belong to the stationary set described above, but that however make it possible to satisfy the constraints. We now describe the set of all states that satisfy all of the constraints in a dynamic perspective, including non stationary trajectories. The set of bioeconomic states from which there exist intertemporal paths respecting the whole constraint is called the *viability kernel* of the problem.[4]

The viability kernel for the Nephrops fishery is represented in Fig. 4.
This viability kernel represents the ``goal'' of the recovery paths, i.e. the set of states the system must reach to ensure a viable exploitation. For any given initial state (S_0, X_0) in the viability kernel, there exists at least one intertemporal decision series $(e(.), \xi(.))$ for which the associated trajectory starting from (S_0, X_0) respects all of the constraints forever. Note that there may be several viable decisions. Another important point is that all admissible decisions are not necessarily viable and may lead the system outside the viability kernel.

The stationary states described in the previous section are particular cases of viable trajectories (that are stationary trajectories, associated to *ad hoc* decisions). If the initial state belongs to the left-bottom hand-side of the viability kernel the resource stock will increase for any viable decision. On the contrary, if the initial state is on the right-up hand-side, the resource stock will decrease whatever viable decision applies.

From the very definition of this viability kernel, for any outside initial state, there are no decisions that make it possible to satisfy the constraints in the long run. For example, any trajectory starting from the upper area of the state's constraint set, at least one of the constraints will be violated in a finite time, whatever decisions apply. The system thus faces a crisis situation if the bioeconomic state is outside the kernel or if the intertemporal path leaves it.

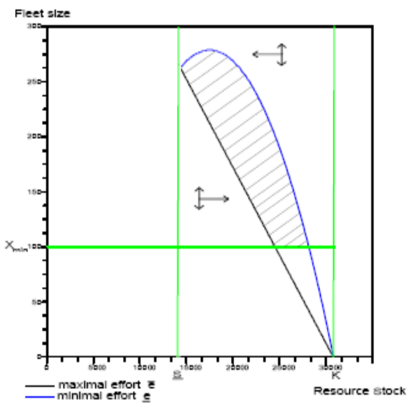


Fig. 3. Viable stationary states (the upper limit corresponds to minimal effort $\underline{e}(S)$, the lower limit to maximal effort $\bar{e}$.

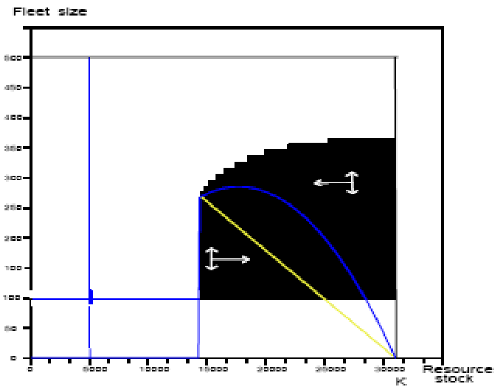


Fig. 4. Viability kernel.

[4] For an introduction to the viability theory, see Aubin (1991). Applications to resource management can be found in Béné et al. (2001), Béné and Doyen (2002) and Martinet and Doyen (2006).

Recovery paths

In this section, we use the above framework of analysis to characterize recovery processes, from situations outside the viability kernel which we call crisis situations, to viable situations. A crisis situation corresponds to configurations that do not make it possible to respect the viability constraints $\mathcal{K}$, namely to satisfy $(S_t, X_t, \xi_t, \pi_t) \in \mathcal{K}$, in the long run. We define the characteristic function χ_{K} as

$$\mathcal{X}_{\mathcal{K}}(S,X,e,\xi) = \begin{cases} 0 \text{ If } (S_t, X_t, \xi_t, \pi_t) \in \mathcal{K} \\ 1 \text{ If } (S_t, X_t, \xi_t, \pi_t) \notin \mathcal{K} \end{cases} \quad (14)$$

Achieving viability in the future: the concept of minimal time of crisis: In the context of this analysis, the issue is to reach the viability kernel in the future. From a theoretical point of view, the characteristic function (eq.14) counts the number of period when viability constraints do not hold true. It can be interpreted as the time spent outside the kernel. A transition phase is then characterized by a time of transition, corresponding to this time. Starting from a given bioeconomic state, various transition phases exist, that reach the kernel more or less quickly.

We define the *minimal* time of crisis as the time spent outside the kernel by the fastest transition phase starting from a given bioeconomic state (the minimal time to reach the target).

Based on this notion of *minimal time of crisis* we are able to define the notion of viability at time *T*, which is the set of states that make it possible to belong to the viability kernel after *T*. For example, the set of states that are viable at time 2 is composed of all states for which the minimal time of crisis is lower than or equal to 2. In particular, the viability kernel defined in the previous section corresponds to viability at time t_0. The formal link between the viability at scale *T* and the minimal time of crisis is developed in Doyen and St-Pierre (1997)

More formally, the minimal time of crisis, i.e. the minimal time spent outside of $\mathcal{K}$ by trajectories starting at *(S,X)*, is defined by the map

$$\mathcal{C}_{\mathcal{K}} = \inf_{\in (e(.),\xi(.))\mathbb{U}} \sum_{t_0}^{\infty} \mathcal{X}_{\mathcal{K}}(S,X,e,\xi) \quad (15)$$

This map is represented for the Nephrops fishery by fig. 5.

By the very definition of the viability kernel, any state outside the kernel (crisis situation) does not make it possible to respect the constraints. All viability constraints thus cannot be respected during the transition phase.

In particular, the recovery strategy associated with the minimal time of crisis may require to close the fishery for a while (there is no effort, i.e. no fishing activity: the capital is not used), along with reducing the fleet size as quickly as possible (given the inertia constraint 7). This entails a strong violation of the minimum profit constraint. As noted before, due to economic and social requirements, transition phases may need to ensure a minimum level of revenue to vessels, even if it is lower than the minimum viable profit.

Recovery paths under constraint: Even if the optimal recovery strategy requires closing the fishery for a while (Clark, 1985), this is not always possible because it neglects fisher's needs to cover some fixed costs or to ensure a minimal activity and revenue. One may thus require a minimum activity during the transition phase, or more specifically, a minimum remuneration of labor and capital.

To take such requirements into account leads to ``softening'' one or several viability constraints during the transition phase. In particular, it is possible to accept that the fishery can face periods where profits from the activity in excess of the opportunity costs of capital and labor are negative, without inducing the definitive shutdown of the activity.

In our model, this possibility is defined by introducing constraints on transition decisions, i.e. by restricting the set of admissible choices such that *e(t)* ensures a minimal profit constraint during the transition phase. We define this constraint π'.

The map representing the transition phases under constraint for the Nephrops fishery is represented in figure 6.

We can compare the various areas with respect to the minimal time of crisis without constraint defined in the previous section. As the admissible decision set is restricted during the transition phase under constraint, it is longer to reach the target (the viability kernel) from any given crisis situation. This means that a same initial state will stand in a farther area of the map (characterized by a greater minimal time of crisis) with the π' constraint on transition decisions.

Moreover, with this constraint, an area appears on the map, from which it is not possible to achieve recovery (the white area on the left hand side in Fig. 6). Thus, for any given initial state, there is a maximum profit constraint on the transition phase for which it is possible to reach the viability kernel in a finite time.

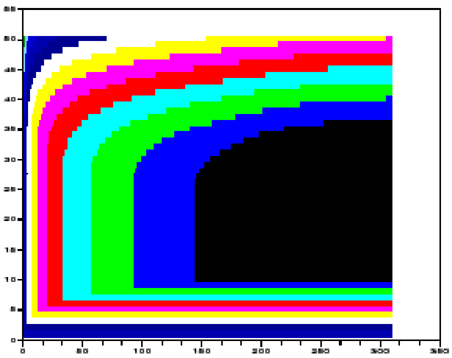


Fig. 5. Scale of viability and minimal time of crisis.

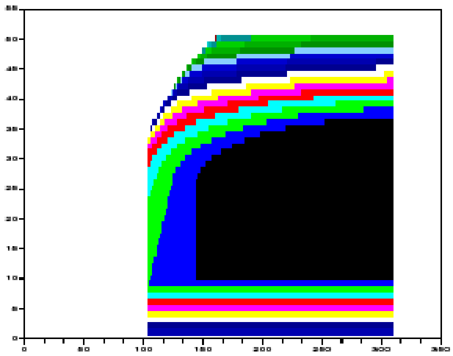


Fig. 6. Transition phases under constraint.

RECOVERING MSY PRODUCTION

In this section, we apply the general framework previously developed to address a particular issue. We examine how to reach a sustainable goal defined as a production in the neighborhood of the MSY, starting from the situation of the Nephrops fishery in 2003.

In particular, we examine the consequences of this production objective on the fleet configuration (number of vessels and profit), and the time needed to reach it. First, we define the viability kernel associated to the MSY production objective, and the associated time of crisis. We then examine how to minimize the transition cost towards this objective state of the fishery.

MSY and viability analysis

We first determine the bioeconomic states that are compatible with MSY. We then examine if these configurations are viable, i.e. respect the viability constraints defined in previous sections.

The *maximum sustainable Yield* is a particular stationary state where the resource regeneration is maximum, such that the sustainable harvesting is maximal too. We consider a production constraint defined as

$$C(t) \geq C_{MSY} \qquad (16)$$

The production of the stock at MSY level is $R_{MSY}=rK/4$. For the application case, we set C_{MSY}=6 000 tons.

Assuming such a minimal production constraint induces *a posteriori* constraints on the resource stock, and on the minimal fleet size.[5] The induced constraint on the resource stock is $S(t) \geq S_{MSY} = K/2$.

In a static perspective, the minimal size of the fleet to ensure MSY production is derived from the definition of catches (eq. 2). We get

[5] A higher production level requires higher capital use.

$$qS_tX_te_t = \frac{rK}{4} \Rightarrow \underline{X}_{MSY}(S) = \frac{rK}{4q\bar{e}}\frac{1}{S}.$$

Thus, at S_{MSY} we have $\underline{X}_{MSY} = r/2q\bar{e}$. In our application, we get a minimum number of vessels equal to 247 boats at the MSY stationary state. With such a fleet size, *per* vessel profit is limited to 150 000 euros. It is lower than the observed average profit in 2003 (about 165 000 euros). Having the MSY production as an objective requires to increase the fleet size and to reduce the per vessel profit with respect to the present situation.

Viability kernel of the MSY production: The first step of the analysis is to define bio-economic states that make it possible to respect the production constraint (16). For this purpose, we apply the viability approach to the system described by dynamics (3) and (6) and constraints (7) and we use the production constraint (16) instead of the economic and social constraints (9) and (10) on the minimal profit and minimal fleet size.

The viability kernel associated with this viability problem is given in Fig. 9. It represents the combinations of stock and fleet size for which there exist viable decisions compatible with the minimum production level.

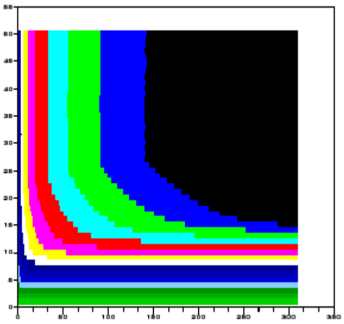


Fig. 9. Biological and economic states allowing to sustain the MSY production.

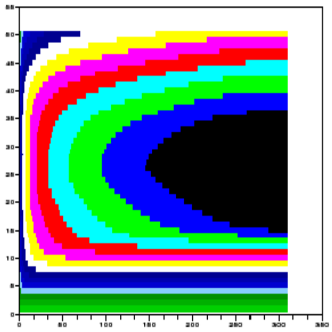


Fig. 10. Viability kernel and minimal time of crisis for viability constraints and MSY production requirement.

We see in figure 9 that a minimum size of the fleet is required to produce at this level. As an increasing stock ensures increasing catches for a given effort level, the bigger the stock is, the less boats are needed.

We now turn to analyze the economic viability of such a production objective. We consider once again the profit constraint π_{min} defined by equation (9). We consider the viability kernel associated with all of the constraints, including the minimal profit per vessel and the minimal production of the ecosystem. This viability kernel and the associated times of crisis are presented in Fig. 10.

Comparing Fig. 9 and Fig. 10, we can see that the profit constraint reduces the set of viable states that make it possible to produce MSY. Stationary states correspond to the resource stock producing MSY. The minimal effort satisfying profit constraint (eq.12) at the MSY stock is

$$\underline{e}(S_{MSY}) = \frac{\pi_{min} + \beta_1}{\frac{p}{\lambda}(1-\tau_d)q\frac{K}{2} - \beta_2} \qquad (20)$$

Using relationship (19), we get the maximal number of vessels sustainable at MSY.

$$\bar{X}(S_{MSY}) = \frac{r\left(\frac{p}{\lambda}(1-\tau_d)q\frac{K}{2} - \beta_2\right)}{2q(\pi_{min} + \beta_1)} \qquad (21)$$

In our case study, we get X_{max}=272 vessels, having an individual effort of 145 days of sea. Combining this result with the minimal fleet size to ensure MSY, we have several possible stationary states, with a number of vessels between 247 and 273 vessels.

Transition phases

As an application, we consider in this section the following sustainability goals:

$$\pi_{min} = 150000 \quad (22)$$
$$C_{min} = C_{MSY} \quad (23)$$

Thus, viability constraints are associated with the MSY production (eq.16) along with a constraint on the individual profit, in order to get it as close as possible to the observed profit.

The viability kernel and minimal time of crisis associated with this viability problem are represented in Fig.11. This viability kernel is smaller than the one ensuring viable profit. Here again, the minimal time of crisis is associated with a shutdown of fishing activity. To take into account social and economic constraints, we consider a minimal profit constraint during the transition phase. We set it at the level of opportunity costs (which is the level we used in the previous section as a minimal profit for economic viability): π'=130 000 euros.

The problem is thus to reach viable states, where sustainability goals are to produce at MSY level, with a maximum individual profits, and limiting the loss during the transition phase (minimal profit covering opportunity costs of the producing factors).

The map on Fig.12 represents the time of crisis under transition constraints.
Such a study show that the set of viable states is reduces and that transitions phases would be longer if a viability constraint on the profit is required during the transition phase.

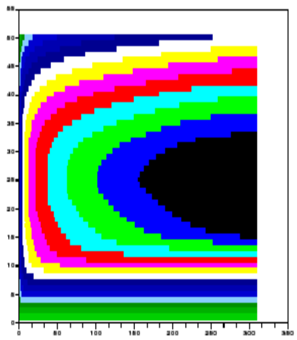


Fig. 11. Minimal time of crisis associated with MSY production level and maximal per vessel profit.

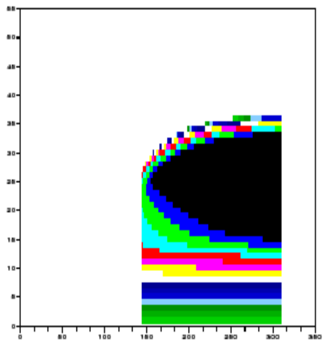


Fig. 12. Transition phases under economic viability constraint to reach MSY production level.

CONCLUSION

In this paper, we examine the viability of a fishery with respect to economic, social and biological constraints. The main constraint is a minimal profit per vessel that must be guaranteed at each time period. We show that requiring such a minimum profit induces a minimal threshold for the natural resource, and thus a stronger constraint on the resource stock than the initial biological constraint. As has already been demonstrated, it is thus possible to reconcile economic and ecological objectives.

We use the viability approach to determine the set of bioeconomic states that make it possible to satisfy the constraints dynamically. This set is called the viability kernel of the problem. Any trajectory leaving this set will violate the constraints in a finite time, whatever decisions apply. The system then faces a crisis situation.

We then study transition phases from crisis situation, i.e. states outside the viability kernel, to viable exploitation configurations. These transitions phases are characterized by the time of transition on the one hand, and the cost of the transition on the other hand. This cost is defined as the difference between a minimum profit ensuring economic viability and the observed profit during the transition phase. We show that the shorter the transition phase is, the higher the transition costs are.

Using this general framework of analysis, we focus on a particular issue, examining how to ensure MSY production for the bay of Biscay Nephrops fishery. We show that such a production requirement implies increasing the fleet size while reducing the per vessel profit. We then characterize transition phases toward desired exploitation patterns. We define how to reach viable states without jeopardizing the economic viability of the fleet. A strong limitation of the analysis presented is that we rely on a biological model that does not take into account the uncertainty on recruitment, which is a critical point to address recovery issues in this fishery. As there is no established stock-recruitment relationship for Bay of Biscay Nephrops, the modeling of recruitment should be addressed in a stochastic framework. This is part of future research to develop the biological part of the model in order to represent the aged-structure of the species along with the uncertainty on recruitment.

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ENDNOTES

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