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Abstract

This paper develops a formal analysis of the recovery processes for a fishery, from undesired to desired levels of sustainable exploitation, using the theoretical framework of viability control. We define sustainability in terms of biological, economic and social constraints which need to be met for a viable fishery to exist. Biological constraints are based on the definition of a minimal resource stock to be preserved. Economic constraints relate to the existence of a minimum profit per vessel. Social constraints refer to the maintenance of a minimum size of the fleet, and to the maximum speed at which fleet adjustment can take place. Using fleet size and fishing effort per vessel as control variables, we identify the states of this bioeconomic system for which sustainable exploitation is possible, i.e. for which all constraints are dynamically met. Such favorable states are called viable states. We then examine possible transition phases, from non-viable to viable states. We characterize recovery paths, with respect to the economic and social costs of limiting catches during the recovery period, and to the duration of this transition period. Sensitivity of each of the constraints to transition costs and time are analyzed. The analysis is applied to a single stock fishery; preliminary results of an empirical application to the bay of Biscay nephrops fishery are presented.

Key words: sustainable fishing, recovery, fishery policies, bio-economic modeling.

JEL Classifications: Q22, C61

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Contents

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1 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 other areas of natural resource management, the *maximin* approach (Solow, 1974; Cairns and Long, 2006) has been used. Instead of maximizing the net present value criteria, this approach considers the maximal level of profit (or utility) that can be sustain forever, given the initial state of the economy. It thus strongly includes an intergenerational equity concern. For example, Tian and Cairns (2006) examine the sustainable management of a renewable resource: the forest on Easter Island. They show that, depending on the initial configuration of the bioeconomic system, a sustainable exploitation pattern would have been possible on the island, with higher population levels and welfare than actually observed (Brander and Taylor, 1998). But this approach still considers only an economic criterion, when sustainable management of renewable resources may require to consider economic, social and environmental criteria together.

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 Saint-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 in section 2, as well as the definition of the economic, biological and social constraints determining the viability of the fishery. Section 3.2 then presents 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 3.3. The specific issue of recovering MSY production levels without jeopardizing the viability of the fishery is addressed in Section . Section 5 concludes.

2 Defining a sustainable fishery

2.1 A bio-economic model of the fishery

In this paper, we consider a single stock fishery, characterized by the size of the fleet $X_t \in [0, \bar{X}] \subset \mathbb{N}^+$, which can evolve in time. The exploited resource is represented by its stock $S_t \in [0, K]$, where K is the carrying capacity of the ecosystem.

The dynamics of the bio-economic system is controlled by the effort $e_t \in [0, \bar{e}] \subset \mathbb{N}^+$ (day of sea per period and per vessel[1]) and the change in the fleet size $\xi_t \in [-\alpha_1, \alpha_2] \subset \mathbb{N}^+$, the number of boats entering or exiting the fleet. We assume that the admissible controls belong to a set $(e, \xi) \in \mathbb{U}$, where $\mathbb{U} = [0, \bar{e}] \times [-\alpha_1, \alpha_2]$.

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

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

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

$$C_t = qS_te_tX_t \tag{2}$$

where q represents the catchability of the resource.

We thus get the dynamics of the resource combining eq. (1) and (2), following Gordon (1954)

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

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 $c_t = C_t/X_t = qS_te_t$ and a discard rate τ_d

$$L_t = (1 - \tau_d)qS_te_t. \tag{4}$$

[1] The maximal day of sea per period $\bar{e}$ represents a technical constraints. In any case, it cannot be more than 365 days per year.

These landings give the gross return for the targeted species which is a part λ of the vessel's total gross return.[2] Vessel profit thus reads

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

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 labour. The size of the fleet evolves according to a decision control ξ_t,

$$X_{t+1} = X_t + \xi_t. \tag{6}$$

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). Its reads

$$-\alpha_1 \le \xi_t \le \alpha_2. \tag{7}$$

This means that levels 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.

2.2 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:

$$S_t \ge S_{min} \tag{8}$$

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.

$$\pi_t \ge \pi_{min} \tag{9}$$

[2] Taking $\lambda = 1$ means that the studied species is the only one exploited by the fleet.

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}:

$$X_t \geq X_{min} \tag{10}$$

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 (eq. 7) can be interpreted as a social and political constraint limiting the number of vessels (and employment) leaving the fleet.[3]

We call this set of constraint $\mathcal{K}$, in the sense that states and controls respecting the entire set of constraints belong to $\mathcal{K}$, which reads

$$\text{Viability constraint (8), (9) and (10) are respected} \Leftrightarrow (S_t, X_t, \xi_t, \pi_t) \in \mathcal{K}$$

Considering the state constraints (8) and (10), viability requires as a necessary condition $(S_t, K_t) \in [S_{min}; K] \times [X_{min}; \bar{X}]$. 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). This result is stated in proposition 1 below, which is proven in the appendix A.2.

Proposition 1 *The minimal resource stock for fishing activity to respect the per vessel profit constraint (9) is*

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

[3] 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.

This induced constraint comes from the fact that a minimal effort is required to satisfy the profitability constraint (9), as proved in the appendix A.2 by the lemma 2. This minimal effort depends on the resource stock as the catches increase with the resource stock.

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

This minimum effort is represented in Figure 1 with respect to the resource stock. The vertical asymptote represents the limit $S_\flat$ from which fishing effort has a positive marginal value (Appendix A.2, Lemma 1). The fishing effort required to satisfy the profit constraint is a decreasing function of the stock size. [4] 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.

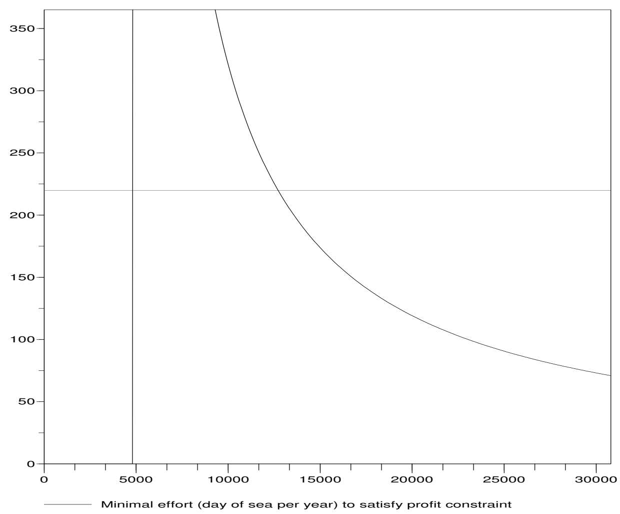


Fig. 1. Minimal effort $\underline{e}(S_t)$ required to satisfy profit constraint (9), with respect to the stock size.

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

[4] It tends towards infinity in the neighborhood of $S_\flat$.

The analysis is applied to a case study: the Bay of Biscay Nephrops fishery (ICES area VIII). Parameters estimation procedures are detailed in the appendix A.1.

Parameters values and constraints 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.

3 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.

3.1 Open access versus *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. The dynamics are illustrated in Figure 2.

Figure 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 intretemporal 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, as claimed in lemma 1, the individual effort will be maximum.

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 profit 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.[5] 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 minimum (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 behaviour is determined by maximizing the intertemporal sum of discounted fleet profits, with respect to the allocation of the fishing effort through time, which reads

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

where δ represents the social discount rate or, from a microeconomic perspective, the opportunity cost of capital.[6] In the general framework, the optimal

[5] 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 been exhausted as the catches per unit of effort become very small when the stock is reduced to low levels.

[6] For the numerical application, we set an interest rate equals to 5%

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, allowing 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.

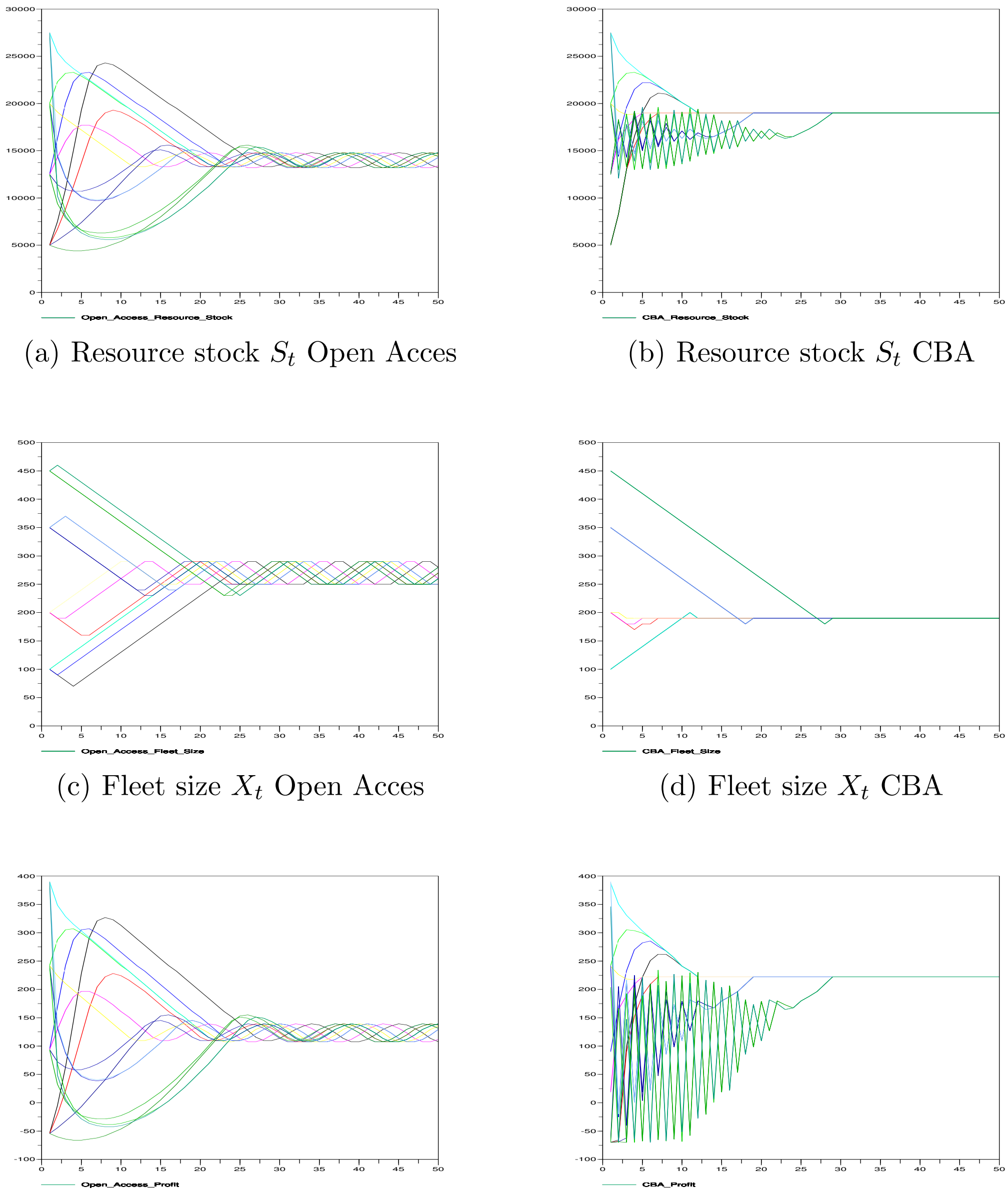
Nevertheless, there is no “bang-bang” strategy as there is an inertia in the capital (fleet size) adjustement. When the fleet size is smaller than the targeted size, the stock size and the profit level evolve smoothly, with increasing or decreasing profit, depending on the resource stock (the larger the stock, the more harvesting and profit). On the contrary, when the fleet size is large and require a long time period for adjustement, 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. [7]

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.

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 analyse the viability of the fishery by defining intertemporal paths of harvesting that satisfy all the constraints defined in the previous section simultaneously.

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



(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).

3.2 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).

The set of bioeconomic states from which there exist intertemporal paths respecting the whole constraint is called the *viability kernel* of the problem. A description of the viability theory and viable control approach is provided in the appendix A.3, along with a formal definition of this viability kernel.

Viable stationary states A first analysis relies on the definition of viable stationary states. These states are characterized by

$$\begin{aligned} S_{t+1} &= S_t \\ X_{t+1} &= X_t \end{aligned}$$

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 maximun 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 Figure 3. The inner area corresponds to possible stationary states that satisfy all the constraints, including the profitability constraint.

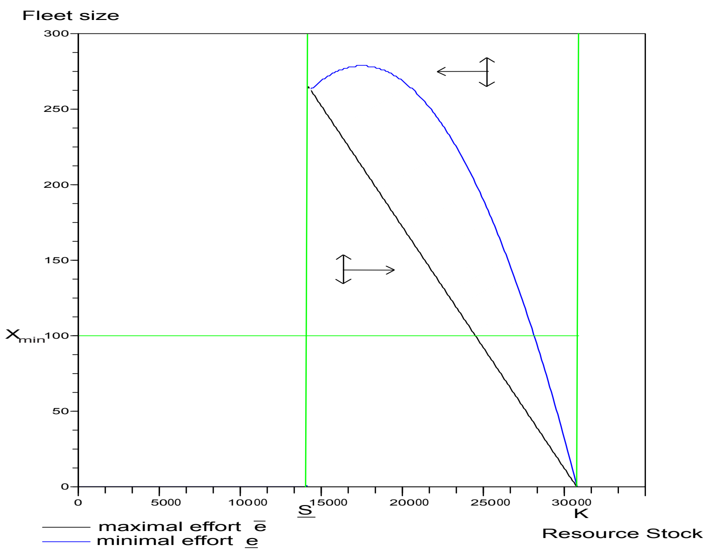


Fig. 3. Viable stationary states (the upper limit corresponds to minimal effort $\underline{e}(S)$, the lower limit to maximal effort $\bar{e}$.

We can see on Figure 3 that there is a maximal sustainable size for the fleet, when the effort is minimum. 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 less yield 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.

Viable states 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. General statements on this viability kernel and the way it is computed are presented in appendix A.3.

The viability kernel for the nephrops fishery, using parameter values presented in section 4 is represented in Figure 4.

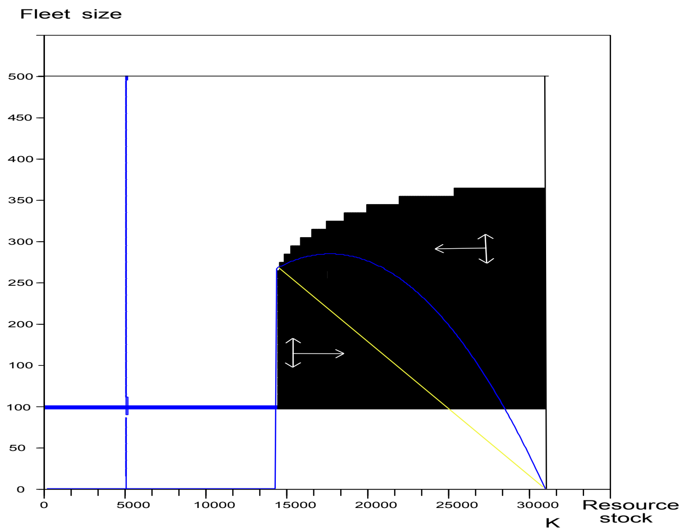


Fig. 4. Viability kernel.

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 exist 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 strating from the upper area of the state's constraint set, i.e. for any $(S_0, X_0) \in [S_{min}; K] \times [X_{min}; \bar{X}]$, at least one of the constraint will be violated in a finite time, wathever decisions apply. The system thus faces a crisis situation if the bioeconoic state is outside the kernel or if the intertemporal path leaves it.

3.3 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, namely to satisfy $(S_t, X_t, \xi_t, \pi_t) \notin \mathcal{K}$, in the long run. We define the characteristic function $\mathcal{X}_{\mathcal{K}}$ as

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

3.3.1 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 (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 characterised 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 Saint-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

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

This map is represented for the nephrops fishery by figure 5.

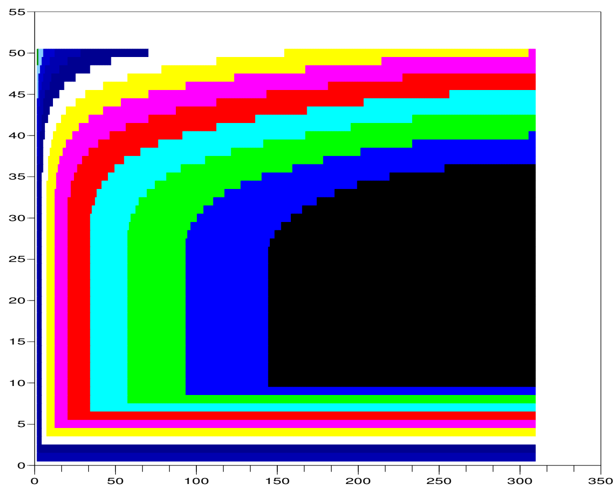


Fig. 5. Scale of viability and minimal time of crisis.

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.

3.3.2 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 labour 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 labour 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 $\tilde{\pi}$.

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

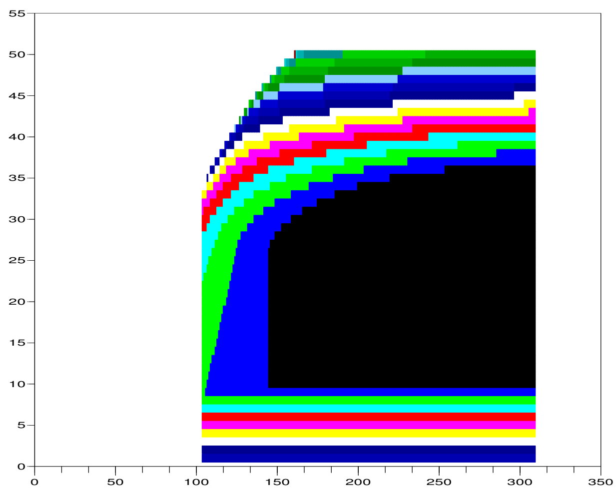


Fig. 6. Transition phases under constraint.

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 $\tilde{\pi}$ 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 on Figure 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.

4 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.

4.1 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

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

The production of the stock at MSY level is

$$R_{MSY} = \frac{rK}{4} \tag{17}$$

For the application case, we set $C_{MSY} = 6000$ tons.

Assuming such a minimal production constraint induces *a posteriori* constraints on the resource stock, and on the minimal fleet size.[8] The induced constraint on the resource stock is

$$S(t) \geq S_{MSY} = \frac{K}{2}. \tag{18}$$

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

$$qS_tX_te_t = \frac{rK}{4} \Rightarrow \underline{X}_{MSY}(S) = \frac{rK}{4q\bar{e}}\frac{1}{S}. \tag{19}$$

Thus, at S_{MSY} we have $\underline{X}_{MSY} = \frac{r}{2q\bar{e}}$. In our application, we get a minimum number of vessels equal to 247 boats at the MSY stationary state. With such a fleet size, the 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 (10) and (9) on the minimal profit and minimal fleet size. We apply the framework proposed in section 3.3.

The viability kernel associated with this viability problem is given in Figure 7. It represents the combinations of stock and fleet size for which there exist viable decisions compatible with the minimum production level.

We see in figure 7 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 analyse 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 Figure 8.

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

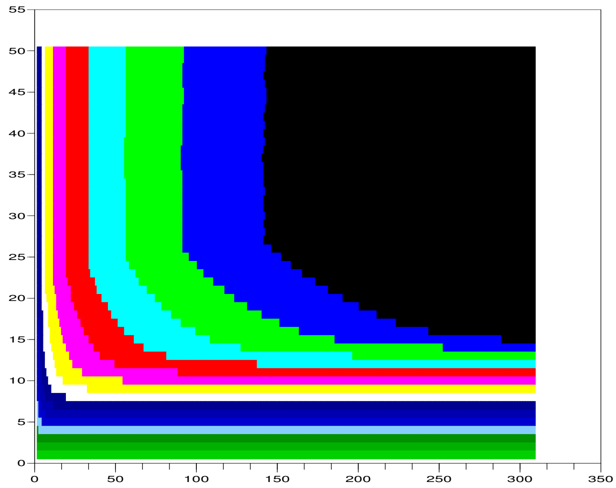


Fig. 7. Biological and economic states allowing to sustain the MSY production.

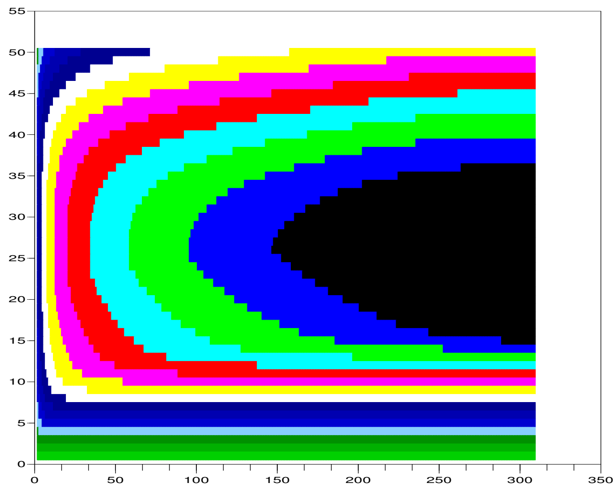


Fig. 8. Viability kernel and minimal time of crisis for viability constraints and MSY production requirement.

Comparing Figure 7 and Figure 8, we can see that the profit constraint reduces the set of viable states that make it possible to produce MSY. Stationary states correpond to the resource stock producing MSY. The minimal effort satisfying profit constraint (eq. 12) at the MSY stock is

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

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

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

In our case study, we get $\bar{X} = 373$ 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 373 vessels.

4.2 Transition phases

As an application of the results of section 3.3, we consider in this section the following sustainability goals :

$$\pi_{min} = 150000 \tag{22}$$
$$C_{min} = C_{MSY} \tag{23}$$

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 is represented in Figure 9.

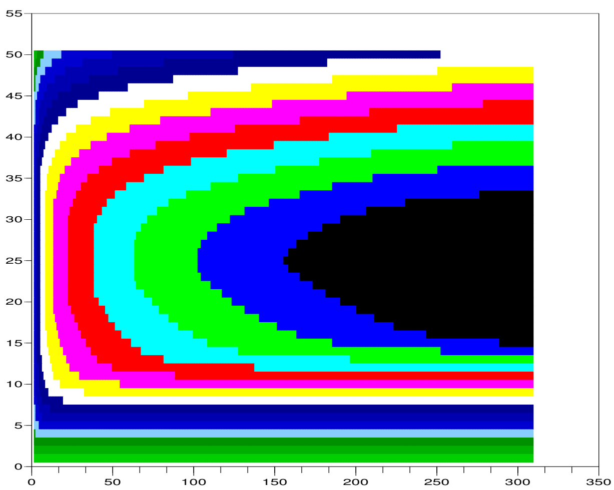


Fig. 9. Minimal time of crisis associated with MSY production level and maximal per vessel profit.

We can see on Figure 9 that the 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): $\tilde{\pi} = 130000$ 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 Figure 10 represents the time of crisis under transition constraints.

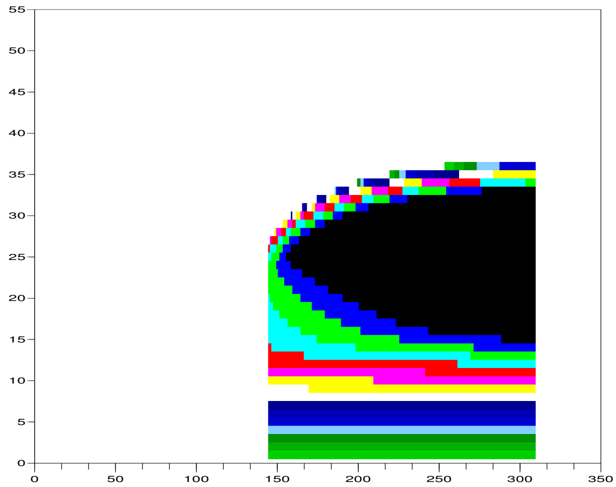


Fig. 10. Transition phases under economic viability constraint to reach MSY production level.

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.

5 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 minimal 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 Annexe

A.1 Parameters of the case study: the Bay of Biscay Nephrops fishery (ICES area VIII)

All along the paper, numerical illustrations are provided, based on an empirical application to the bay of Biscay nephrops fishery. The numerical model has been calibrated with commercial time-series.

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 (Hilborn and Walters, 1992). Figure A.1 represents observed and predicted CPUE.

Fig. A.1. Fitting of observed and predicted CPUE in the biological parameters estimation model.

Economic parameters are estimated using costs and earnings data collected by the Fisheries Information System of Ifremer via surveys of individual vessel owners.

A.2 Individual economic behavior

In this appendix, we detail individual optimal behavior. We first determine the effort level that maximizes the profit of vessels.

Lemma 1 *If the resource stock is greater than a level $S_\flat = \frac{\beta_2}{\frac{p}{\lambda}(1-\tau_d)q}$, the optimal fishing effort of a vessel is its maximum possible effort $e(t) = \bar{e}$. Else, the optimal effort is* 0*.*

Proof of Lemma 1 *The profit, defined by eq. (5) is*

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

At a given time t, and for the resource stock S_t, taking the profit derivative with respect to the effort level e_t leads to

$$\frac{\partial \pi}{\partial e} = \frac{p}{\lambda}(1-\tau_d)qS_t - \beta_2$$

which is positive if the resource stock S_t is greater than a threshold $S_\flat$ such that

$$S_\flat = \frac{\beta_2}{\frac{p}{\lambda}(1-\tau_d)q}.$$

The optimal individual effort thus follows a “bang-bang” strategy : no fishing if $S_t < S_\flat$ and a maximum activity $\bar{e}$ if $S_t > S_\flat$. In our illustrative case, this value is $S_\flat = 4,075$ tonnes, which is lower than the resource constraint S_{min}. We will thus consider that it is always optimal to fish as much as possible.

We then define the minimum effort level ensuring the minimum profit π_{min}. For this purpose, we examine instantaneous condition on the effort e_t for constraint (9) to be satified at time t, given stock S_t.

Lemma 2 *The minimum effort e_t insuring profit π_{min} at a given level of stock S_t is given by*

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

Proof of Lemma 2 *At a given level of stock S_t at time t, for constraint (9) to be satisfied, we must have*

$$\Big(p(1-\tau_d)qS_te_t\Big)\frac{1}{\lambda}-(\beta_1+\beta_2e_t)\geq\pi_{min}$$

which leads to

$$e_t\geq\frac{\pi_{min}+\beta_1}{\frac{p}{\lambda}(1-\tau_d)qS_t-\beta_2} \tag{A.2}$$

Hence the minimum effort $\underline{e}(S_t)$.

We are now able to prove proposition 1

Proof of Proposition 1 *Given the profit equation*

$$\pi_t=pqS_te_t-(\beta_1+\beta_2e_t)\geq\pi_{min}$$

and combinig the optimal effort from Lemma 1 along with the maximum effort bound $\bar{e}$, we get

$$S_t\geq\frac{\pi_{min}+(\beta_1+\beta_2\bar{e})}{pq\bar{e}}. \tag{A.3}$$

Hence $\underline{S}$.

Note that at this stock level $\underline{S}$, we have $\underline{e}(\underline{S})=\bar{e}$, which means that the minimum effort to satisfy the constraint is the maximum effort.

A.3 About the viability analysis

The viability approach and viable control framework (Aubin, 1991) focuses on intertemporal feasible paths. It consists in the definition of a set constraints that represents the "good health" or by extension the effectiveness of the system at any moment, and in the study of conditions which allow these constraints to be satisfied along time including both present and future. So, it leaves the optimality framework and focus on the respect of constraints of controlled dynamic systems; in this way, various criteria are considered instead of an unique optimization criterion.

More formally, the viability approach deals with dynamic systems under state and control constraints. The aim of the viability method is to analyse compatibility between the possibly uncertain dynamics of a system and state or control constraints, and then to determine the set of controls or decisions that would prevent this system from going into crises i.e. from violating these constraints. We refer for instance to Martinet and Doyen (2006); Béné et al. (2001); Doyen and Béné (2003) for some stylised models in other contexts.

More specifically, in the environmental context, viability may imply the satisfaction of both economic and environmental constraints. In this sense, it is a multi-criteria approach sometimes known as "co-viability". Moreover, since the viability constraints are the same at any moment and the term horizon is infinite, an intergenerational equity feature is naturally integrated within this framework.

The viability kernel: a definition The viability kernel is the set of bioeconomic states that make it possible to satifsy the constraints throughout time, given the dynamics. It is defined as the set of all states (S_t, X_t) from which there is at least one feasable path $(S(.), X(.))$, associated with admissible decisions $(e(.), \xi(.))$, that satisfies all the constraints along time. It means that, starting from a state outside the viability kernel, there are no decisions that make it possible to satisfy the constraints forever (at least one of the constraints won't be respected after some finite time T, whatever decisions apply).

Formally, for our problem, the viability kernel is defined by

$$Viab = \left\{ (S_0, X_0) \;\middle|\; \begin{array}{l} \exists (e(.), \xi(.)) \text{ and } (S(.), X(.)), \text{ starting from } (S_0, X_0) \\ \text{satisfying dynamics (3) and (6)} \\ \text{and constraints (7), (8), (9) and (10) for any } t \in \mathbb{N}^+ \end{array} \right\} \tag{A.4}$$

In the general mathematical framework, this set can alternatively be empty, the whole state constraint set $\mathcal{K}$, or even a strict part of the initial state constraint domain. The viability kernel captures an irreversibility mechanism. Indeed, from the very definition of this kernel, every state lying outside the viability kernel violates the constraints in finite time, no matter what the decisions applied. This situation means that crisis is unavoidable. For instance, the extreme case where the viability kernel is empty corresponds to a hopeless configuration. An empty kernel means that there are no sustainable paths for the described system, i.e. no paths that respect the set of constraints representing sustainability. It is then necessary to "modify" the problem (to consider a different set of sustainability constraints) to be able to define some sustainable decisions or states.

This kernel is the set of initial fleet configurations and resource stocks from which it is possible to define acceptable regimes of exploitation satisfying all of the constraints throughout time. Therefore, the viability kernel provides the *ex post* viability constraints that are the "true" constraints to be satisfied by the bioeconomic system to be sustainable, in the sense that if a state is out this kernel, there are no decisions that make it possible to satisfy the constraints throughout time.

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