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# Defining viable recovery paths toward sustainable fisheries

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**Abstract**

This paper develops a formal analysis of the recovery processes for a fishery, from crisis situations to desired levels of sustainable exploitation, using the theoretical framework of viable 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 guaranteed 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 first 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 and 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. The analysis is applied to a single stock fishery; preliminary results of an empirical application to the bay of Biscay nephrops fishery are presented. In this case, transitions paths derived from the viability approach are compared to an open-access scenario and an optimal (with respect to an intertemporal discounted profit sum) harvesting scenario.

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

*JEL Classifications:* Q22, C61

**Contents**

## 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 higher sustainable levels of fish stocks, catches, and revenues from fishing.

The problems posed by fisheries restoration are dynamic in nature: beyond the issue of choosing 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. (a etoffer)

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 such as fishing effort, and looking at a single optimization criteria such as the net present value of the expected benefits derived from harvesting. Alternative approaches have been based on the simulation of specific adjustment trajectories for given bioeconomic systems, according to predetermined scenarii, and on their *a posteriori* evaluation with respect to various criteria Smith (1969); Mardle and Pascoe (2002); Holland and Schnier (2006). However, sustainable management of renewable resources requires the consideration of economic, social and environmental criteria together. (!! Changer les citations !!)

In this paper, we develop a formal analysis of the recovery paths for a fishery, based on viable control theory. The weak invariance 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” of the system at any moment, and in the study of conditions which allow these constraints to be satisfied along time. 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, an intergenerational equity feature is naturally integrated within this framework and connections with the sustainability issue are pointed out in Martinet and Doyen (2006). From the ecological viewpoint, the so-called population viability analysis (PVA) (Morris and Doak, 2003) and conservation biology have concerns close to viable control by focusing on extinction process generally within a stochastic framework. Cury et al. (2005) advocate the use of the viability framework to ecosystem approach in fisheries and it has been used for renewable resources management in Béné et al. (2001); Doyen and Béné (2003); Eisenack et al. (2006). In particular, the viable control approach allows us to characterize 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 viable levels of exploitation. We propose a discussion on the viability of various recovery trajectories, including the estimated historical trajectory, and simulated economic exploitation trajectories. Numerical analysis have been implemented in Scilab using the IFREMER datas.

The paper is organized as follows. The fishery is described in section 2. The simplified model of the bay of Biscay nephrops fishery used for the analysis is developped (2.1). The economic, biological and social constraints determining the viability of the fishery are defined (2.2), and the parameters are described for our case study (2.3). In section 3, we develop the theoretical framework that allows us to analyse the conditions under which the viability constraints can be satisfied throughout time (3.1), and to study recovery processes from crisis situations (3.2). We use this framework in section 4 to study some recovery paths from the historical 1994 crisis situation. 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 every year $t$ by the biomass $B_t$ of the exploited resource stock and the size of the fleet $K_t$ which both evolve with time. The dynamics of the bio-economic system is controlled by the effort $e_t$ corresponding to the days at sea per period and per vessel and the change in the fleet size $\xi_t$ namely the number of boats entering or exiting the fleet.

We use a discrete 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

$$R(B_t) = rB_t \left(1 - \frac{B_t}{B_{\text{sup}}}\right), \tag{1}$$

where $B_{\text{sup}}$ is the carrying capacity of the ecosystem.

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

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

where $q$ represents the catchability of the resource. We thus get the dynamics of the resource combining eq. (1) and (2), following Gordon (1954)

$$B_{t+1} = B_t + R(B_t) - C_t = B_t + rB_t \left(1 - \frac{B_t}{B_{\text{sup}}}\right) - qB_te_tK_t \tag{3}$$

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 $\tau_d$

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

These landings give the gross return for the targeted species which is a part $\lambda$ of the vessel's total gross return.[1] Vessel profit thus reads

$$\pi_t = \Big(p(1 - \tau_d)qB_te_t\Big)\frac{1}{\lambda} - (\omega_f + \omega_ve_t) \tag{5}$$

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

where $p$ is an exogenous resource price that is considered constant. $\omega_f$ represents fixed costs and $\omega_v$ a per effort unit cost. This "profit" thus represents the gross return minus the "technical" exploitation costs.[2] The production factors (capital and labour) are remunerated with this profit.

The production structure is assumed to be slowly flexible, in terms of both capital and labor. The size of the fleet evolves according to a decision control $\xi_t$,

$$K_{t+1} = K_t + \xi_t. \tag{6}$$

To take into account the inertia of capital, the change of the fleet size is limited. A maximum number $\xi_{\text{sup}}$ of vessels can enter the fishery in any time period, which represents some technical constraints. The number of vessels exiting the fleet in any time period can not exceed $\xi_{\text{inf}}$, due to social and political constraints (see below). Such rigidities are captured by conditions

$$-\xi_{\text{inf}} \leq \xi_t \leq \xi_{\text{sup}}. \tag{7}$$

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. Moreover, the effort is bounded by the maximal day at sea per period[3] $e_{\text{sup}}$ and we write the technical constraints

$$0 \leq e_t \leq e_{\text{sup}}. \tag{8}$$

### *2.2 Sustainable exploitation patterns*

Sustainability of the exploitation is defined by a set of biological, economic and social constraints that have to be respected throughout time.

**Biological constraints:** In order to preserve the renewable resource, a minimal resource stock $S_{\text{min}}$ is considered. It is related to a quasi extinction threshold in the sense that the regeneration of the stock is not guaranteed below this level:

$$B_t \geq B_{\text{min}} \tag{9}$$

**Economic constraints:** An individual economic constraint on the vessel performance is also considered: profit per vessel is required to be greater than

[2] For example, fixed costs include . They are not related to the number of days at sea. Variable costs include fuel, ice and food expenditures. They are correlated to the number of days at sea.

[3] In any case, it cannot exceed 365 days per year.

a threshold $\pi_{\min}$ for economic units to be viable.

$$\pi_t \geq \pi_{\min} \tag{10}$$

This minimal profit is defined such as to ensure remuneration of both capital and labor, at least at their opportunity costs. It can also be set as a sustainability goal ensuring levels 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 $K_{\min}$:

$$K_t \geq K_{\min} \tag{11}$$

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 during one time period. 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.

**An induced effort constraint:** It turns out that a minimal effort is required to satisfy the profitability constraint (10), 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.

$$e_t \geq \underline{e}(B_t) = \frac{\pi_{\min} + \omega_f}{\frac{p}{\lambda}(1-\tau_d)qB_t - \omega_v} \tag{12}$$

**An induced stock constraint:**
Considering the state constraints (9) and (11), viability requires that the state $(S_t, K_t)$ lies in the desirable set $[B_{\min}, +\infty[\times[K_{\min}; +\infty[$. Nevertheless, it does not mean that this constraint set makes it possible to satisfy the profitability constraint (10). In particular, the biological configuration for which it is possible to have a profitable fishing activity can be determined. It turns out that the profit constraint (10) also generates stronger limitations on stock size

than the biological constraint (9). In particular, a minimal resource stock for fishing activity to respect the per vessel profit constraint (10) is given by

$$B_t \geq \underline{B} = \frac{\pi_{\min} + (\omega_f + \omega_v e_{\sup})}{\frac{p}{\lambda}(1-\tau_d) q e_{\sup}}. \tag{13}$$

This result is stated and proved within the appendix A.2.

### *2.3 A case study: the Bay of Biscay Nephrops fishery*

To illustrate the method and results, the analysis is applied to a case study: the Bay of Biscay Nephrops fishery (ICES area VIII). Appendix A.1 describes how parameters have been estimated. Parameters values and constraints levels are given there. In particular, it appears that the minimal profit per vessel in our stylized model of the fishery would be 130,000 euros per period.

Note that the case study has been choosen for illustrative purposes, and the described stylised facts may not be interpreted as policy recommandations. Actually, the Bay of Biscay Nephrops fishery faces selectivity, bycatch and discarding issues. The resource is age-structured and it matters a lot in both the resource dynamics and the economic valorisation of the catches. The uncertainty on recruitement plays another important role in the sustainability of the fishery. We developped a more realistic model of this fishery in Doyen et al. (2006).

In 2003, the fleet was composed by 235 vessels with an average profit of 165,000 euros. The resource stock was estimated at about 18,600 tons. The average number of days at sea was 203. The catches were estimated at 5,769 tons. Viability constraints, as we defined them, were thus met at that year. Nevertheless, in the 90's, the resource stock decreased, and the per vessel profit was lower than the profitability constraint. The estimated resource stock reached its lowest level in 1994, about 14,000 tons, and the per vessel profit was 78,000 euros this year. The fishery thus faced a crisis period (at least from the economic point of view) and seems to have recovered from it.

Our purpose it to propose a theoretical framework in which we can study both the conditions for a fishery to be viable, and the dynamic paths allowing the fishery to recover from a crisis situation.

## 3 Characterizing viable situations and crisis situations

In this section, we describe the theoretical framework that will allow us to deal both with the sustainable exploitation configuration and the crisis situations, and the way to recover from such situations.

### *3.1 The viability kernel and viable harvesting strategies*

The aim of this section is to define state configurations, including resource stock and fleet size, which are compatible with the viability constraints which have been defined. The question is to determine whether the dynamics 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), (9), (10) and (11). The set of bioeconomic states from which there exist intertemporal paths respecting the whole constraint is called the *viability kernel* of the problem. It corresponds to the sustainable exploitation configurations.

**Viable states** Formally, for our problem, the viability kernel is defined by

$$\text{Viab} = \left\{ (B_0, K_0) \left| \begin{array}{l} \exists (e(.), \xi(.)) \text{ and } (B(.), K(.)), \text{ starting from } (B_0, K_0) \\ \text{satisfying dynamics (3) and (6)} \\ \text{and constraints (7), (9), (10) and (11) for any } t \in \mathbb{N}^+ \end{array} \right. \right\} \tag{14}$$

The viability kernel for the nephrops fishery (using parameter values presented in appendix A.1) is represented on Fig. 1 (black area). The hystorical trajectory is represented in red. Note that the situation by 1994 is not viable in the sense that it does not belong to the viability kernel.

**Particular viable states: stationary states** Among all viable states, there are particular states that allow the dynamics (for associated *ad hoc* exploitation decisions) to follow stationary trajectories.[4] Among these sta-

[4] These stationary states are characterized by $B_{t+1} = B_t$ and $K_{t+1} = K_t$ which leads to $\xi_t = 0$ and $R_t = C_t$. This last statement is equivalent to $e_t K_t = \frac{r}{q}\left(1 - \frac{B_t}{B_{\text{sup}}}\right)$. Such a relation induces admissible stationary states whenever all the constraints, including the profitability constraint hold true. Extreme cases correspond to maximun effort $e_{\text{sup}}$ on the one hand (which leads to a linear relationship between the fleet size and the resource stock), and minimum effort $\underline{e}(B_t)$ on the

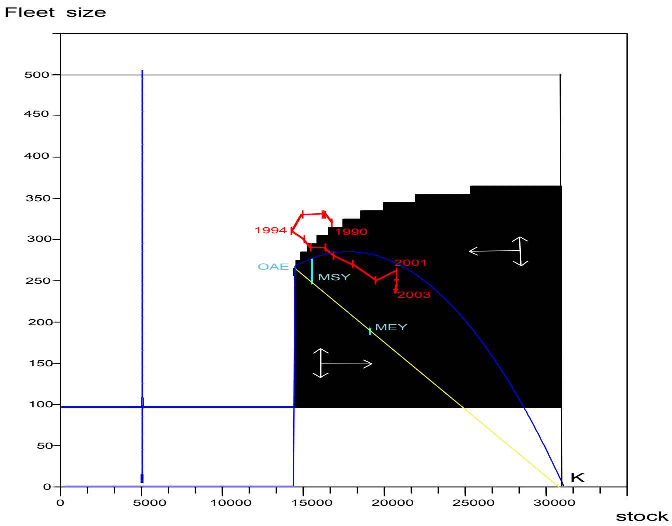


Fig. 1. The viability kernel, the stationary states and the historical dynamics.

tionary states, some are of particular interest:

- The *Open Access Equilibrium* (OAE) correponds to the equilibrium stationary state reached by a open access system, when vessels can freely enter or leave the fishery with respect to the profit level, i.e. if it covers the opportunity costs represented by constraint (10), and choose their effort level.
- The *Maximum Economic Yield* (MEY) correponds to the stationary state in which the total profit of the fleet is maximal. It correponds to the resource stock for which the marginal productivity of the resource stock in price equals the marginal costs of catching this extra unit, and to the production structure that minimizes the costs, i.e. the minimal fleet size as we have fixed costs and positive productivity of the effort.
- The *Maximum Sustainable Yield* (MSY) corresponds to the resource stock associated with the largest regeneration $R(B_{MSY})$. Various stationary states are possible, depending on the fleet size and the per vessel catches (the total

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other hand. Hence we obtain the conditions on fleet size and resource stock

$$\frac{r}{\underline{q}e(B)}\left(1-\frac{B}{B_{\text{sup}}}\right) \leq K \leq \frac{r}{qe_{\text{sup}}}\left(1-\frac{B}{B_{\text{sup}}}\right) \tag{15}$$

which can occur if stock $B$ is larger than $\underline{B}$. These two frontiers are represented on Fig. 1. The inner area corresponds to possible stationary states that satisfy all the constraints, including the profitability constraint. Outside the stationary state area, if the initial state belongs to the bottom left hand side of the viability kernel the resource stock will increase for any viable decisions. On the contrary, if the initial state is on the top right hand side, the resource stock will decrease whatever viable decisions apply.

catches being constant).

Note that there is a maximal sustainable size for the fleet. It correponds to the same stock as in the MEY state, but with a maximal fleet sharing the global effort, just to ensure the minimal profit constraint (10).

For any given initial state $(B_0, K_0)$ in the viability kernel, there exists at least one intertemporal decision series $(e(.), \xi(.))$ for which the associated trajectory starting from $(B_0, K_0)$ respects all of the constraints forever. Note that there may exist several viable decisions. Another important point is that all a priori admissible decisions are not necessarily viable and some of them may lead the system outside the viability kernel or induce exploitation patterns that do not respect all of the viability constraints.

For example, the historical modelled dynamics entered the viability kernel in 1996. It means that it would have been possible to follow a viable exploitation trajectory, in the sense that there existed decisions such that all of the constraints could have been met. Nevertheless, the actual exploitation decisions from the 1996 state were not viables as the profit constraint was not met. [5]

### *3.2 Outside the kernel: crisis situations*

The viability kernel represents the "goal" for recovery paths starting from initial states outside the kernel, i.e. the set of states the system must reach to make a viable exploitation path possible.

From the very definition of the viability kernel, from any initial state outside the kernel, there are no decisions that make it possible to satisfy the constraints in the long run. At least one of the constraints will be violated in a finite time, whatever the decisions are. The system thus faces a crisis situation if the bioeconomic state is outside the kernel or if the intertemporal path leaves it.

To recover from such crisis situations, the bioeconomic state must reach the viability kernel. It is possible only if the decisions do not respect the constraints during some time period in order to lead the bioeconomic state towards the viable states.

[5] See appendix A.1 for the datas of the hystorical path.

### 3.2.1 *Minimal time of crisis*

In the context of this analysis, the issue is to reach the viability kernel from a state outside the kernel. From a theoretical point of view, the number of period when viability constraints do not hold true 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. Hence, the viability kernel defined in the previous section corresponds to viability at time 0. The formal link between the viability at scale $T$ and the minimal time of crisis is exposed in Doyen and Saint-Pierre (1997).

More formally, the minimal time of crisis, i.e. the minimal time spent outside the viability kernel by trajectories starting at $(B_0, K_0)$, is defined by the value function

$$\mathcal{C}(B_0, K_0) = \inf_{(B(.),K(.),e(.),\xi(.)) \text{ admissible}} \sum_{t=0}^{\infty} \mathbf{1}(B_t, K_t, e_t, \xi_t) \tag{16}$$

where $\mathbf{1}$, the characteristic function that counts the number of period when viability constraints do not hold true, is defined by

$$\mathbf{1}(B, K, e, \xi) = \begin{cases} 0 & \text{if } (B, K, e, \xi) \text{ satisfy constraints (9), (10) and (11)} \\ 1 & \text{otherwise} \end{cases} \tag{17}$$

and path $(B(.), K(.), e(.), \xi(.))$ is said to be admissible whenever it satisfies dynamics and control constraints (3), (6) and (7) while starting from $(B_0, K_0)$. This value function is represented for the nephrops fishery by Fig. 2.

By the very definition of the viability kernel, any state outside the kernel (crisis situation) does not make it possible to respect the constraints. Some viability constraints thus must be unsatisfied 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

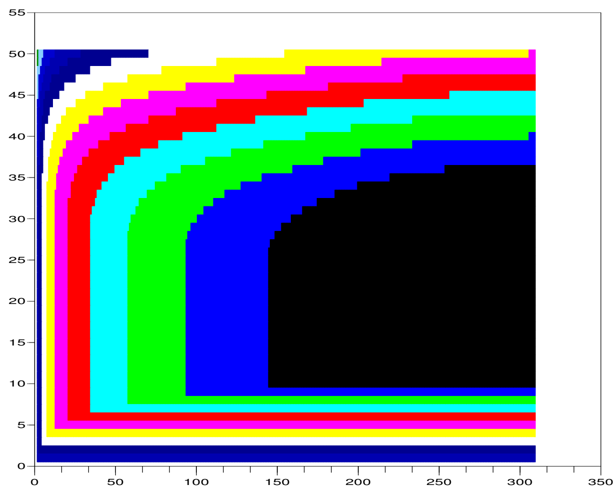



Fig. 2. Scale of viability and minimal time of crisis.

the minimum profit constraint. As noted before, due to economic and social requirements, it may be desirable to have some minimum level of revenue ensured to vessels during the transition phases, even if it is lower than the minimum viable profit.

### *3.2.2 Minimal time of crisis under transition profit 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.

Taking such requirements into account requires "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 a total 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 3.

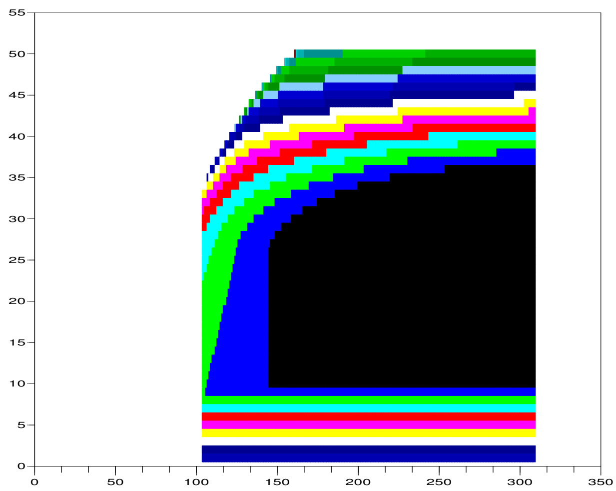



Fig. 3. Transition phases under constraint.

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 Fig. 3). 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 from a crisis situation

In this section, we characterize recovery processes from crisis situations to viable situations. As mentioned previously, the situation observed in year 1994 was critical for the fishery since it does not belong to the viability kernel. Consequently we compute some recovery trajectories from the 1994 initial state and compare these different paths to the estimated historical path which is used as a benchmark. We consider four recovery strategies:

- the open access fishery;
- the (economically) optimal intertemporal harvesting;

- the minimal time of crisis;
- the minimal time of crisis under a transitional profit constraint.

### *4.1 The four scenarii*

#### *4.1.1 Open access*

The open access case corresponds to a situation in which vessels can freely enter and exit the fishery, subject to the inertia constraints (7) described above, and choose their individual effort level. In that case, as claimed in lemma 1, the individual effort will be maximum: the individual optimal behavior in a non regulated fishery is to have the maximal admissible effort, which reads

$$e_t^{OA} = e_{\sup}. \tag{18}$$

We consider that, if individual profit is greater than the minimal profit $\pi_{\min}$, the fleet size increases as new vessels enter the fishery. On the contrary, if the individual profit is lower than 90% of the $\pi_{\min}$ 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. In our representation of the Open Access regime, the dynamics of capital, i.e. the fleet size, evolves as follows

$$\xi_t^{OA} = \begin{cases} \xi_{\sup} & \text{if} \quad \pi_t \geq \pi_{\min} \\ -\xi_{\inf} & \text{if} \quad \pi_t \leq 0.9\pi_{\min} \end{cases} \tag{19}$$

#### *4.1.2 Discounted dynamic maximum economic yield*

As a second scenario, we consider a regulated fishery where the decision maker optimizes the discounted intertemporal profit of the fleet.

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 and the management of the fleet size, which reads

$$\max_{e(\cdot),\xi(\cdot)} \sum_{t=0}^{\infty} \frac{1}{(1+\delta)^t} K_t \Big( pqB_t e_t - (\omega_f + \omega_v e_t) \Big) \tag{20}$$

where $\delta$ represents the social discount rate or, from a microeconomic perspective, the opportunity cost of capital. [6] In the general framework, the optimal solution of such a problem (Clark, 1990) is to reach an optimal steady state

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

following a “bang-bang” strategy (or most rapid approach). In the case presented here, there is no “bang-bang” strategy, given the inertia in capital (fleet size) adjustement.

### *4.1.3 Minimal time of crisis and transition phase under constraints*

The two harvesting scenarios considered above lead to paths that do not have concern for the viability constraints. 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.

We then compare the historical path and the classical open access and optimal harvesting strategies with the recovery paths using viable control, within both minimal time of crisis and transition phase under a minimal profit constraint. In both cases, we limit the speed of the fleet size adjustment to 5 boats per year, which is a ”softer” adjustment than the historical path.

We first compute the minimal time of crisis associated with the 1994 bioeconomic state, and the recovery path that minimizes that time of crisis. For this purpose, we use the results of section 3.2.1. This path implies a shut down of the fishery during one time period (with a negative profit) in order to restore the stock, and then an exploitation pattern making it possible to provide the minimal profit to the whole fleet. The reduction of the fleet size is less strong than in all other simulated cases, including the historical path, the open access regime and the optimal economic harvesting.

In a second step, we determine the recovery path under a minimal profit cosntraint

$$\pi_t \geq \tilde{\pi} \tag{21}$$

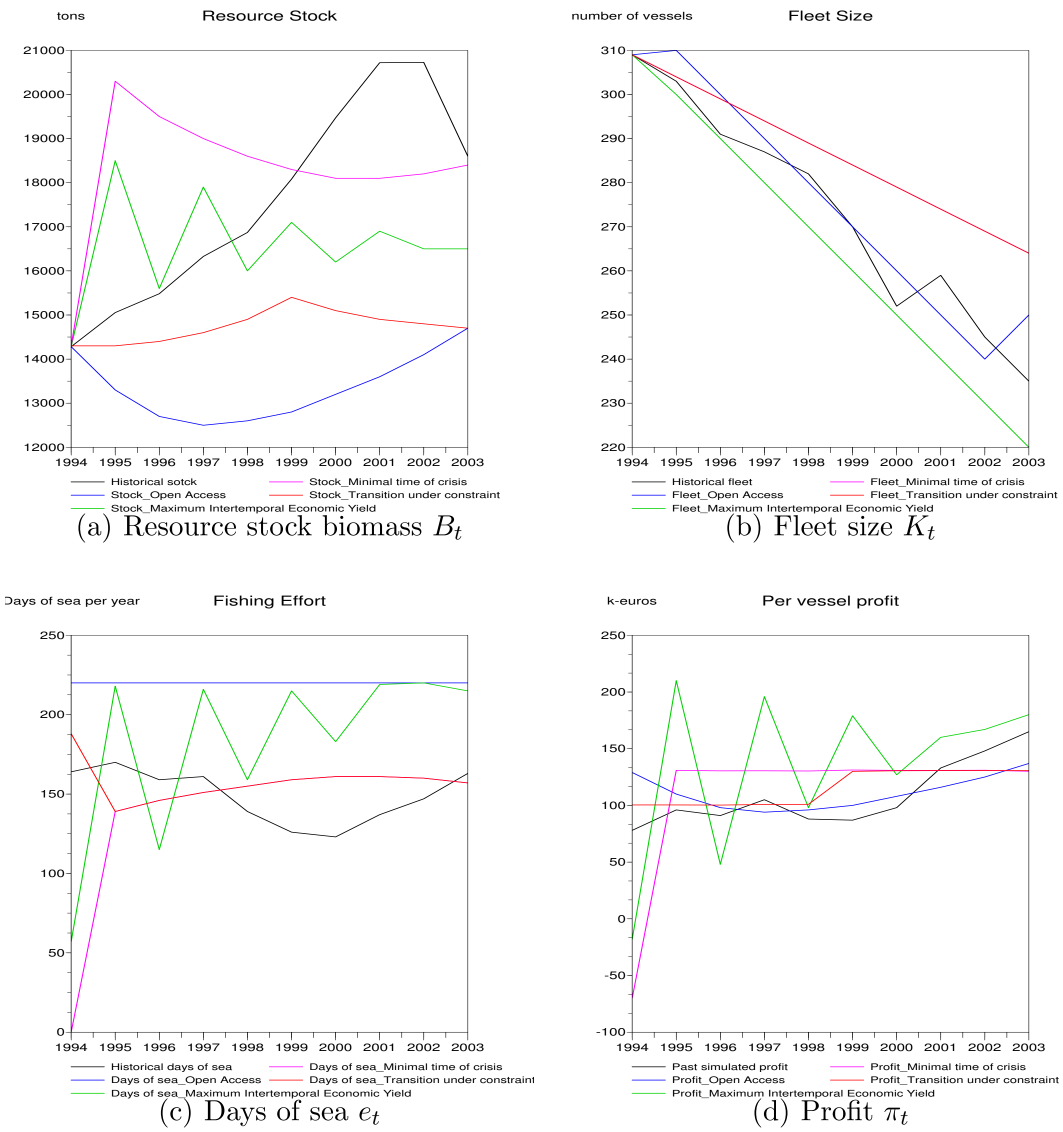
with $\tilde{\pi} = 100,000$ euros. We use the result of section 3.2.2.

The transition phase is longer as the fishery is not shut down and a minimal profit is ensured all along the recoveray process. However, the profit is higher than the historical one, emphazing the interest of the approach.

## *4.2 Compared trajectories*

From an historical point of view, the dynamics of the Nephrops fishery from the 1994 situation (lowest estimated biomass) was characterized by a strong reduction of the fleet size, along with a recovery of the resource stock. From 1994 to 2001, the profit was lower than the viability threshold $\pi_{\min} = 130,000$ euros. During these ten years, even if the bioeconomic state reached the viability kernel quickly (and thus would have make it possible to satisfy the profit constraint) the profit was lower that the constraint level until 2001. It illustrates the fact that not all decisions are viable inside the viability kernel. The fishery did not statisfied the viability constraint duraing this period actually.

We consider as a reference the estimated historical trajectory followed by the fishery since 1994, represented on Fig. 1. We propose to examine what could have been the results of our approach in such a crisis situation.




(a) Resource stock biomass $B_t$

(b) Fleet size $K_t$

(c) Days of sea $e_t$

(d) Profit $\pi_t$

Fig. 4. Recovery strategies (and the historical path) from the 1994 crisis situation.

According to the Open Access model, it appears that an open access exploitation from the 1994 situation would have led to both a decrease of the resource stock and the fleet size, with a recovery at the end of the simulation period. Maximizing the intertemporal economic profit would have led to some "bang-bang" path with alternance of high and low exploitation level, tending towards the stationary state characterizing the Maximum Economic Yield.

Viable recovery path defined using the framework we have developped in the paper leads to softer recovery paths. In both minimal time of crisis and transition under minimal profit constraint cases, the reduction of the fleet size is less strong ans the recovery time is shorter than in the other scenarii.

A more straighforward way to exhibit the difference between all these paths is to compute the global profit for the fishery. In the viability framework, the per vessel profit is not increasing in the long run but the fleet size is more important. The global production of the fishery is then high. Fig. 5 illustrates this result.

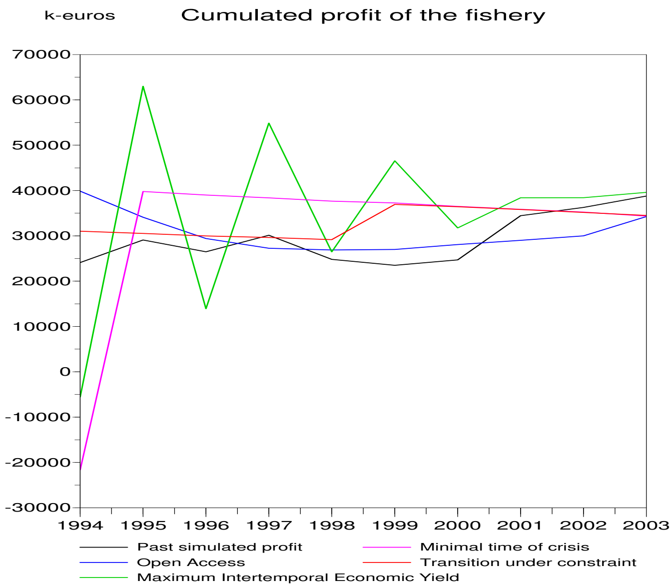



Fig. 5. Fleet's total annual profit during the transition phase.

## 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.

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.

To illustrate these theoretical results, we compute recovery paths from the historical crisis of 1994 in the Bay of Biscay Nephrops fishery. We compare two recovery paths given by our approach with the modelled historical path, the simulated open access exploitation regime and the economically optimal intertemporal harvesting. The first recovery path we describe relies on the minimal time of crisis. The transition is short but requires to shut down the fishery. We then propose a recovery path ensuring a minimal profit during the transition phase. The recovery time is longer but a higher profit is guaranteed to the whole fleet.

The case study results should be discussed carefully. We do not claim to provide any usefull advices on the managment of the Bay of Biscay Nephrops fishery. The case study has only an illustrative purpose. We study the viability of this fishery in a more realistic model including the age structure of the resource, environmental uncertainty on recruitment and ecological interactions, in Doyen et al. (2006).

## 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 analysis is applied to a case study: the Bay of Biscay Nephrops fishery (ICES area VIII). 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 CPUE, given the observed CPUE. 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.

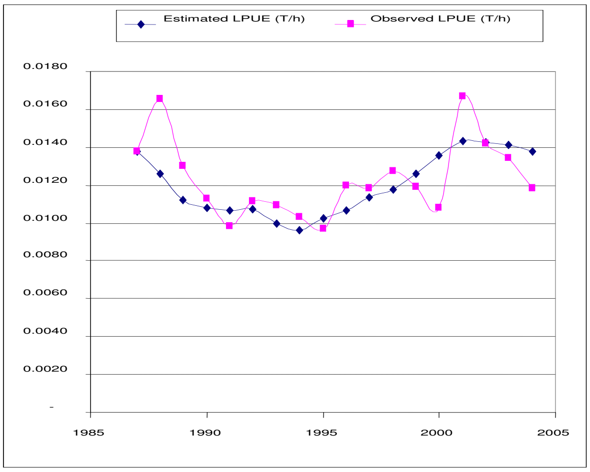



Fig. A.1. Fitting of observed and predicted CPUE in the biological parameters estimation model.

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

Parameters values are as follows.

| Parameter | value | Constraint | level |
|---|---|---|---|
| $r =$ | 0.78 | $S_{\min} =$ | 5,000 tons |
| $B_{\sup} =$ | 30800 tons | $K_{\min} =$ | 100 vessels |
| $q =$ | $72.10^{-7}$ $\mathrm{j}^{-1}$ | $\pi_{\min} =$ | 130,000 euros |
| $p =$ | 8,500 euros per tons | $\xi_{\inf} =$ | 10 |
| $\omega_f =$ | 70,000 euros per year | $\xi_{\sup} =$ | 10 |
| $\omega_v =$ | 377 euros per day of sea | | |
| $e_{\sup} =$ | 220 days | | |
| $\tau_d =$ | 33% | | |
| $\lambda =$ | 43% | | |

The historical path (with the estimated biomass) is summurazed in the following table.

| | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 |
|---|---|---|---|---|---|---|---|---|---|---|
| Estimated resource Stock (tons) | 14281 | 15054 | 15482 | 16328 | 16871 | 18082 | 19471 | 20721 | 20728 | 18600 |
| Observed fleet size | 309 | 303 | 291 | 287 | 282 | 270 | 252 | 259 | 245 | 235 |
| Observed fishing effort (days at sea per vessel - mean) | 164 | 170 | 159 | 161 | 139 | 126 | 123 | 137 | 147 | 163 |
| Profit (keuros per vessel - mean)) | 78 | 96 | 91 | 105 | 88 | 87 | 98 | 133 | 148 | 165 |

### *A.2 Proofs*

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* $B_\flat = \frac{\omega_v}{\frac{p}{\lambda}(1-\tau_d)q}$, *the optimal fishing effort of a vessel is its maximum possible effort* $e(t) = e_{\sup}$. *Else, the optimal effort is* 0.

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

$$\pi_t = \Big(p(1-\tau_d)qB_te_t\Big)\frac{1}{\lambda} - (\omega_f + \omega_v e_t).$$

*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*

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

*which is positive if the resource stock $B_t$ is greater than a threshold $B_\flat$ such that*

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

The optimal individual effort thus follows a "bang-bang" strategy : no fishing if $B_t < B_\flat$ and a maximum activity $e_{\text{sup}}$ if $B_t > B_\flat$. In our illustrative case, this value is $B_\flat = 4,075$ tonnes, which is lower than the resource constraint $B_{\min}$. 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 $\pi_{\min}$. For this purpose, we examine instantaneous condition on the effort $e_t$ for constraint (10) to be satified at time $t$, given stock $B_t$.

**Lemma 2** *The minimum effort $e_t$ insuring profit $\pi_{\min}$ at a given level of stock $B_t$ is given by*

$$\underline{e}(B_t) = \frac{\pi_{\min} + \omega_f}{\frac{p}{\lambda}(1-\tau_d)qB_t - \omega_v} \tag{A.1}$$

**Proof of Lemma 2** *At a given level of stock biomass $B_t$ at time t, for constraint (10) to be satisfied, we must have*

$$\Big(p(1-\tau_d)qB_te_t\Big)\frac{1}{\lambda} - (\omega_f + \omega_v e_t) \geq \pi_{\min}$$

*which leads to*

$$e_t \geq \frac{\pi_{\min} + \omega_f}{\frac{p}{\lambda}(1-\tau_d)qB_t - \omega_v} \tag{A.2}$$

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

**Lemma 3** *The minimal resource stock for fishing activity to respect the per vessel profit constraint (10) is*

$$\underline{B} = \frac{\pi_{\min} + (\omega_f + \omega_v e_{\text{sup}})}{\frac{p}{\lambda}(1-\tau_d)qe_{\text{sup}}}. \tag{A.3}$$

We now prove lemma 3

**Proof of Lemma 3** *Given the profit equation*

$$\pi_t = pqB_te_t - (\omega_f + \omega_v e_t) \geq \pi_{\min}$$

*and combining the optimal effort from Lemma 1 along with the maximum effort bound $e_{\text{sup}}$, we get*

$$B_t \geq \frac{\pi_{\min} + (\omega_f + \omega_v e_{\text{sup}})}{\frac{p}{\lambda}(1-\tau_d)qe_{\text{sup}}}. \tag{A.4}$$

*Hence $\underline{B}$.*

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

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## References

Aubin, J.-P., 1991. Viability theory. Birkhauser, Springer Verlag.

Béné, C. and Doyen, L., 2000. Storage and viability of a fishery with resource and market dephased seasonnalities. Journal of Environmental Resource Economics, 15:1-26.

Béné, C., Doyen, L. and Gabay, D., 2001. A viability analysis for a bio-economic model. Ecological Economics, 36:385-396.

Boncoeur, J., Alban, F., Guyader, O. and Thébaud, O., 2002. Fish, fishers, seals and trourits: economic consequences of creating a marine reserve in a multi-species, multi-activity context. Natural Resource Modelling, 14:-.

Brander, J. and Taylor, S., 1998. The simple economics of Easter Island: A Ricardo-Malthus model of renewable resource use. American Economic Review, 88:119-138.

Cairns, R. and Van Long, N., 2006. Maximin: a direct approach. Environment and Development Economics, forthcoming.

Clark, C.W., 1985. Bioeconomic Modelling and Fisheries Management. John Wiley and Sons: New York.

Clark, C.W., 1990. Mathematical Bio-economics: the optimal management of renewable resources. Second edition, John Wiley and Sons: New York.

Clarke, F.H., Ledyaev, Y.S., Stern, R.J. and Wolenskip, R., 1995. Qualitative properties of trajectories of control systems: a survey. Journal of Dynamical Control System, 1:1-48.

Cury, P., Mullon, C., Garcia, S. and Shannon, L.J., 2005. Viability theory for an ecosystem approach to fisheries. ICES Journal of Marine Science, 62:577-584.

Doyen, L. and Béné, C., 2003. Sustainability of fisheries through marine reserves: a robust modeling analysis. Journal of Environmental Management, 69:1-13.

Doyen, L., Martinet, V. and Thébaud, O., 2006. Co-viability of Nephrops and Hake fisheries in the Bay of Biscay. mimeo, Ifremer.

Doyen, L. and Saint-Pierre, P., 1997. Scale of viability and minimal time of crisis. Set-valued Analysis, 5:227-246.

Eisenack, K., Sheffran, J. and Kropp, J., 2006. The Viability Analysis of Management Frameworks for fisheries. Environmental modelling and assessment, 11:69-79.

Food and Agriculture Organization, 2004. The state of World Fisheries and Aquaculture. FAO, Sofia.

Garcia, S. and Grainger, J.R., 2005. Gloom and doom? The future of marine capture fisheries. Phil. Trans. R. Soc. B., 360:21-46.

Gordon, H.S., 1954. The economic theory of a common property resource: the fishery. Journal of Political Economy, 82:124-142.

Heal, G., 1998. Valuying the Future: Economic theory and sustainability. Columbia University Press, New-York.

Hilborn, R. and Walters, C., 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. International Thomson Publishing.

Holland, D. S. and Schnier, K. E., 2006. Modeling a Rights Based Approach to the Management of Habitat Impacts of Fisheries. Natural Resource Modeling, forthcoming.

Martinet, V. and Doyen, L., 2006. Sustainability of an economy with an exhaustible resource: a viable control approach. Resource and Energy Economics, forthcoming.

Martinet, V. and Thébaud, O., 2006. On the possibility to combine viability and productivity objectives in the recovery programs for fisheries. mimeo, Ifremer.

Mardle, S. and Pascoe, S., 2002. Modelling the effects of trade-offs between long run and short run objectives in the North Sea. Journal of Environmental Management, 65:49-62.

Morris, W.F. and Doak, D.F., 2003. Quantitative Conservation Biology: Theory and Practice of Population Viability Analysis. Sinauer Associates.

Schaefer, M.B., 1954. Some aspects of the dynamics of populations. Bull. Int. Am. Trop. Tuna Comm., 1:26-56.

Smith, V., 1969. On Models of Commercial Fishing. Journal of Political Economy, 77:181-196.

Solow, R., 1974. Intertemporal use of exhaustible resources and intergenerational equity. Review of Economic Studies, 49:29-45.

Tian, H. and Cairns, R., 2006. Sustainable Development of Easter Island? working paper, Mc Gill University (2006 - February $13^{rd}$).

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