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The triple bottom line: Meeting ecological, economic and social goals with Individual Transferable Quotas

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Le triple résultat : Concilier des objectifs écologiques, économiques et sociaux en présence de quotas individuels et transférables

Résumé

Cet article analyse le fonctionnement d'un système de management d'une ressource renouvelable fondé sur des quotas individuels et transférables en présence d'agents hétérogènes sur leurs coûts et leurs coefficients de capture. Dans un modèle bio-économique dynamique, nous déterminons sous quelles conditions, le décideur d'une pêcherie peut satisfaire durablement des objectifs de conservation de la ressource, d'efficience économique et de maintien de l'activité de pêche. Nous montrons que la viabilité des stratégies de capture totale autorisée dépend du degré d'hétérogénéité des exploitants de la ressource, du niveau initial et de la dynamique du stock. En particulier, pour un montant de stock initial, nous calculons l'effort maximum possible pour un groupe donné d'exploitants et nous calculons le nombre maximum d'exploitant actifs possible pour un niveau d'effort garanti. Nous illustrons nos résultats à la pêcherie de la langoustine dans le Golfe de Gascogne.

Mots-clés : Ressource renouvelable, Soutenabilité, Capture Totale Autorisée, Quotas Individuels Transférables, Maximin, ensemble de faisabilité

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Keywords: Renewable resource; Sustainability; Total allowable catch; Individual and transferable quotas, maximin, feasibility set

JEL : Q22

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The triple bottom line: Meeting ecological, economic and social goals with Individual Transferable Quotas

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Abstract

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1. Introduction

Numerous stocks of renewable resources are under extreme pressure worldwide. Nowhere is this more obvious than in marine fisheries (Garcia & Grainger, 2005). A key reason for this is the common pool status of marine fish stocks, which in the absence of dedicated access regulations, leads to the existence of incentives for fishing firms to invest in fishing capacity beyond collectively efficient (Gordon, 1954). This results in increased pressure on regulating agencies to accept higher exploitation rates of fish stocks, sometimes beyond sustainable levels. It has led major to the recognition that access regulations are an indispensable complement to traditional conservation regulations, in guiding resources use towards more sustainable paths that respect the ecological, economic and social goals of the triple bottom line (FAO, 2008).

Total Allowable Catch (TAC) limitations have been used extensively as conservation measures in fisheries management, as a way to keep annual harvest of fish resources to levels ensuring the long term sustainability of fish stocks and fisheries. These approaches have however proved insufficient to ensure the economic health of fisheries, because without dedicated catch shares "race to fish" conditions led to encourage short-term economic views, driving fishers to continually increase their fishing capacity, and leading to economic inefficiency (Kompas *et al*, 2004). Restricting access to fisheries and allocating shares of the TAC as secure harvesting privileges to fishers has been proposed as a way of solving this problem (Grafton *et al*, 2006; Branch, 2008). Assigning harvest rights is expected to create an incentive for fishers to minimize the cost and effort associated with catching their TAC share while at the same time choosing fishing strategies that maximize their revenue (Grafton *et al*, 2006; Hamon *et al*, 2009). With costs and fishing abilities varying among fishers, the addition of transferability of individual quotas (ITQs) allows fishers to choose between continuing to fish or transferring (by sale or lease) their quota holdings to other, more efficient, fishers. ITQs thus offer a decentralized method of allocating catch possibilities within fisheries which should promote efficient resource use (Clark, 1990). Reviews of the experience with ITQs in fisheries have shown that they are increasingly being adapted, and that this has been associated with improved status of fish stocks and levels of catches (see e.g. Newell *et al.* (2005) for the New Zealand case, or Costello *et al* (2008)).

In contexts where excess capacity in the fishery exists, introducing ITQs should lead to a decrease in fishing capacity as catch privileges are transferred to the more efficient fishers (Kompas & Che, 2005). Although an expected (and to some extent sought for) impact, this effect has turned out to be one of the key points of debate on the opportunity and effectiveness of ITQ approaches to access regulation in fisheries (Pinkerton & Edwards, 2009). Indeed, an immediate consequence of allowing individual quotas to be transferred in contexts where excess capacity existed was a rapid reduction in the nominal fishing capacity, as measured by, e.g. the number of registered vessels and fishermen in a fishery[1], but also of the number of active fishers and firms. The resulting concentration of fishing privileges in the hands of smaller groups, and reduced size of fishing activities in coastal areas have been considered as an important social consequence of management schemes in which ITQs have been adopted (Copes, 1986). In New Zealand Newell *et al.* (2005) reported an overall decline in the number of market participants after the launch of the ITQ system in 1986. This social dimension has indeed become one of the first and foremost debated dimensions of moving to tradeable catch privileges in fisheries. In some cases, these expected social impacts are considered important enough that they will outweigh the expected ecological and economic benefits of the regulations, leading to the feasibility of their implementation being questioned. The EU consultation on "rights-based" fisheries management in the new common fisheries policy illustrates this point (Anonymous, 2007).

There have been several approaches to modeling ITQs in fisheries, ranging from analytical approaches based on simplified models of a fishery (Clark, 2006; Heaps, 2003) and Linear Programming approaches (Lanfersieck & Squires, 1992), through models that use numerical simulation (Dupont, 2000; Guyader, 2002; Guyader & Thebaud, 2001; Little *et al*, 2009). Despite the fact that social considerations may have a strong influence on the possibility for policy makers to adopt ITQs as access regulation measures, these have only rarely been explicitly included as an objective or a constraint in the traditional bio-economic modeling approaches. This is the case for instance in Heaps (2003) who examined how a change in the biomass of the fish stock affects the number of participants in a fishery managed with a TAC and ITQs. Guyader & Thebaud (2001) considered the impact of social factors regarding distributional issues in determining participation of fishing firms in a fishery and the associated quota market. Fulton *et al* (2010) considered the role of social networks in the operation of fisheries quota markets. However, little work has been done on the interaction between the social objectives and the economic and biological objectives which a policy maker may pursue in an ITQ dynamic setting.

[1] In a number of cases, however, this was shown to merely reflect the eradication of latent fishing capacity and fishing licences.

The aim of this paper is specifically to address the tradeoffs between the conservation, economic efficiency and social objectives in an ITQ managed system. To deal with this issue, we develop a dynamic bio-economic model coupled to a weak invariance (Clarke *et al*, 1995) or viable control method (Aubin, 1990). This method focuses on inter-temporal feasible paths, and aims at identifying the conditions that allow desirable objectives or constraints to be fulfilled over time, considering both present and future states (Bene *et al*, 2001; Baumgartner & Quaas, 2009; Martinet, 2010). As emphasized in Martinet & Doyen (2007) or DeLara & Doyen (2008), viable control and weak invariance is closely related to the maximin (Rawlsian) approach with respect to intergenerational equity. This approach has been applied to renewable resources management and especially to fisheries (see, e.g. Bene *et al* (2001); Eisenack *et al* (2006); Martinet *et al.* (2007)), but also to broader (eco)-system dynamics (Cury *et al*, 2005; Doyen *et al*, 2007). Relationships between sustainable management objectives and reference points as adopted in the ICES precautionary approach are discussed in DeLara *et al* (2007). Here this approach allows us to exhibit the feasibility conditions under which a manager can achieve economic, social and biological objectives in a fishery managed under ITQs, considering both present and future states of the renewable resource system.

The paper is structured as follows. Section 2 is devoted to the description of the dynamic bio-economic model together with the profitability and social constraints. Section 3 provides the results related to the feasible quota policies, the maximum number of active users and their effort with respect to the level of agent's heterogeneity and the level of the resource. An application to the nephrops fishery in the Bay of Biscay illustrates the results in section 4. The last section concludes.

2. The bio-economic model

2.1. The resource dynamics

A renewable resource is described by its state (e.g. biomass or density) $x(t) \in I\!R$ at time t. If the amount removed $Q(t)$ is caught at the beginning of each time step, the dynamics of the exploited resource $x(.)$ is given by the escapement function:

$$x(t+1) = f(x(t) - Q(t)) \tag{1}$$

where f is assumed continuous, increasing and zero at the origin. Since the amount caught cannot exceed the resource stock, a scarcity constraint holds:

$$0 \leq Q(t) \leq x(t). \tag{2}$$

2.2. The ITQ market:

At the beginning of each period t, a regulator allocates a total allowable catch (TAC) among the n agents (vessels). The supply of quota is:

$$Q(t) = \sum_{i=1}^{n} Q_i^-(t)$$

where $Q_i^-(t)$ is the initial amount of quota given to agent i. We note $Q_i(t)$ the amount of quota held by agent i after trade. We assume that quotas can freely be traded on a lease market and that inter-temporal trade of quotas is not allowed[2]. The demand for quota is derived as the sum of the optimal amount of harvest of the n agents:

$$H^*(t) = \sum_{i=1}^{n} H_i^*(t).$$

The quota market clearing condition is given by

$$Q(t) = H^*(t). \tag{3}$$

Agents are assumed to be price takers in the output market. The quota price is denoted by $m(t)$ and the price of the resource by p. The quota demand of an agent is obtained by maximizing its profits with respect to its effort $E_i(t)$ (measured in day at sea) under the constraint that its amount of harvest $H_i(t)$ is equal to its quota demand $Q_i(t)$. Profit is defined as:

$$\Pi_i(E_i(t), x(t)) = pH_i(t) - C_i(E_i(t)) - m(t)(H_i(t) - Q_i^-(t)). \tag{4}$$

The harvest function and the quadratic cost function inspired by Clark (2006) (p 163) are given by:

$$H_i(t) = q_i E_i(t) x(t) \tag{5}$$
$$C_i(E_i) = c_{0,i} + c_{1,i} E_i + \frac{c_{2,i}}{2} E_i^2 \tag{6}$$

[2]The question of the initial allocation of ITQs is beyond the scope of the paper.

where q_i is the catchability constant and $c_{0,i}$, $c_{1,i}$ and $c_{2,i}$ the cost parameters. The agents are supposed to optimize their individual profit as follows:

$$\max_{E_i \geq 0} \Pi_i(E_i, x(t)).$$

Applying first order optimality conditions and assuming for a while that the optimal effort $E_i^*(t)$ of agent i is positive, we obtain the individual effort

$$E_i^*(t) = \frac{1}{c_{2,i}} \left((p - m(t))\, q_i x(t) - c_{1,i} \right) \tag{7}$$

and the associated amount of harvest

$$H_i^*(t) = q_i E_i^*(t) x(t) = \frac{1}{c_{2,i}} \left((p - m(t))\, q_i x(t) - c_{1,i} \right) q_i x(t).$$

The demand for quota is the sum of individual harvests across all agents

$$H^*(t) = \sum_{i=1}^{n} H_i^*(t) = x(t) \left[(p - m(t))\, x(t) \sum_{i=1}^{n} \frac{q_i^2}{c_{2,i}} - \sum_{i=1}^{n} \frac{c_{1,i} q_i}{c_{2,i}} \right].$$

Setting

$$\alpha = \sum_{i=1}^{n} \frac{q_i^2}{c_{2,i}}; \beta = \sum_{i=1}^{n} \frac{c_{1,i} q_i}{c_{2,i}}$$

we obtain

$$H^*(t) = x(t) \left[(p - m(t))\, x(t)\alpha - \beta \right]. \tag{8}$$

From the quota market clearing condition (3), the equilibrium quota price is

$$m^*(Q(t), x(t)) = p - \frac{\frac{Q(t)}{x(t)} + \beta}{x(t)\alpha}. \tag{9}$$

Thus, a rise in the quota supply implies a fall in the quota price as $m_Q^*(Q, x) < 0$. An increase in the stock at a given quota supply implies a rise in the amount of harvest for a given effort creating an incentive for all the agents to buy more quotas. This yields an increase for the quota price and $m_x^*(Q, x) > 0$.

If a positive quota demand exists, then a unique quota price $m^*(Q(t), x(t))$ should exist such that $m^*(Q(t), x(t)) \in [0, p[$. When the quota price $m(t)$ is greater than the product price p, the demand for quota is nil. The positivity condition on $m^*(Q(t), x(t))$ implies a state-control constraint

$$x(t)(px(t)\alpha - \beta) \geq Q(t). \tag{10}$$

Combining (10)this with the scarcity constraint (2), we find that this entails the stock constraint

$$x(t) \geq \frac{\beta}{p\alpha}.$$

This result can be compared to the definition of the bionomic equilibrium stock level obtained by Clark (2006, p81) in the case of a homogeneous fishing fleet. In our case, a positive quota price implies that the stock is higher than the level at which the profitability of fishing would be nil, which is the open access equilibrium stock level.

2.3. Social constraint:

The model so far shows conditions which are needed to maximize the economic return from the fishery. Managing for the triple bottom line requires that social and biological constraints also be considered. As shown by Bene *et al* (2001); Martinet *et al.* (2007), the existence of an economic viability constraint in a fishery determines a stock viability constraint, as a minimum stock size required to maintain sustainable levels of catches and rent above a viable level. In an ITQ system, where the initial situation is one of excess capacity, one may observe a reduction in the number of participants leading to social disruption beyond acceptable levels. To account for this, a social constraint may thus be introduced on acceptable management decisions. An extreme approach to this is that the policy ensures that all n agents initially present remain active in the fishery. This will allow the levels of economic impacts associated to the fishery (in terms e.g. of employment on board vessels and land-based activity, and the induced upstream and downstream effects) to be maintained over time. Formally, we introduce a participation constraint representing the management objective of keeping fishers active:

$$E_i^*(t) \geq E_{\text{lim}}, \quad \forall i = 1, .., n \tag{11}$$

where $E_{\text{lim}} > 0$ stands for some guaranteed activity threshold. Substituting the value of m^* given by (9) in the optimal effort E_i^* given by (7) and including this in the social constraint (11) leads to the following expression for this constraint:

$$\left(\frac{\frac{Q(t)}{x(t)} + \beta}{\alpha} \right) q_i - c_{1,i} \geq E_{\text{lim}} c_{2,i}, \quad \forall i = 1, .., n$$

or equivalently

$$\frac{\frac{Q(t)}{x(t)} + \beta}{\alpha} \geq \max_i \frac{c_{1,i} + c_{2,i} E_{\text{lim}}}{q_i} = \lambda. \tag{12}$$

Thus the participation constraint for all users implies a condition relating to the maximum cost-efficiency ratio $c_{1,i}/q_i$ for the least efficient user. If we denote by

$$F_{\text{par}} = \alpha\lambda - \beta \geq 0 \tag{13}$$

the fishing mortality rate applied to the stock[3] associated to participation requirements, the previous constraint (12) reads

$$Q(t) \geq F_{\text{par}} x(t). \tag{14}$$

Based on equations (10) and (14) the following inequality applies

$$F_{\text{par}} \leq \frac{Q(t)}{x(t)} \leq \alpha p x(t) - \beta.$$

From this condition, we derive a critical stock threshold denoted by x_{lim} as

$$x(t) \geq \frac{F_{\text{par}} + \beta}{\alpha p} = \frac{\lambda}{p} = x_{\mathsf{lim}}. \tag{15}$$

Note that such a stock constraint (15) also implies that

$$x(t) > \sup_i \frac{c_{1,i}}{p q_i} = \sup_i x_i^{\text{oa}} \tag{16}$$

where x_i^{oa} is the stock size at bionomic equilibrium with open access for the less efficient user i (Clark, 1990). Hence maintaining all fishers active in a fishery will require that the stock be maintained at a level that is higher than the level at which the least efficient fisher would stop fishing.

3. Results

Based on the above model of the fishery and set of constraints, we consider the case in which a policy maker must decide on a set of TAC policies which ensure that the fishery will respect these constraints. We use the concept of viability kernel to characterize the sustainability of the system as in Bene *et al* (2001); Eisenack *et al* (2006); Martinet *et al.* (2007); DeLara

[3]For $n = 1$, $F_{\text{par}} = 0$ and for $n > 1$, we have $F_{\text{par}} \geq 0$ since

$$\beta \;=\; \sum_{i=1}^{n} \frac{c_{1,i} q_i}{c_{2,i}} = \sum_{i=1}^{n} \frac{c_{1,i}}{q_i} \frac{q_i^2}{c_{2,i}} \leq \sum_{i=1}^{n} \lambda \frac{q_i^2}{c_{2,i}} = \lambda\alpha.$$

et al (2007); DeLara & Doyen (2008); Martinet (2010). This kernel is the feasibility set of initial stock sizes for which an acceptable regime of quotas exists and satisfies the constraints put forward in the previous section. Viable quotas are derived from the viability kernel whenever it is not empty. When it is empty, the problem is re-cast in terms of the maximal number of viable users or the maximal (maximin) guaranteed effort.

3.1. Viability kernel.

The dynamics $x(t+1) = f(x(t) - Q(t))$ is considered in combination with

- The stock constraint (15): $x(t) \geq x_{\mathsf{lim}}$,
- The social or participation constraint (14): $Q(t) \geq F_{\mathrm{par}} x(t)$,
- The economic constraint (10): $Q(t) \leq (p\alpha x(t) - \beta) x(t)$.

The feasibility set of initial states allowing these constraints to be satisfied along time is called the viability kernel. In a infinite horizon context, it can be defined as follows

$$\mathrm{Viab} = \left\{ x_0 \;\middle|\; \begin{array}{l} \text{for any time horizon } T \in \mathbb{N} \\ \text{there exists TAC levels } Q(t) \text{ and resource states } x(t) \\ \text{starting from } x_0 \\ \text{satisfying all the constraints (10), (14), (15) and dynamics (1)} \\ \text{for time } t = 0, 1, \ldots, T \end{array} \right\}. \tag{17}$$

As explained in DeLara & Doyen (2008) or Doyen and De Lara (2010), a dynamic programming structure underlies this viability kernel. We use this property for the proofs of the following propositions as detailed in section 6.

According to the values of F_{par} and the associated x_{lim}, several cases can be distinguished. We introduce the notation $\sigma(x)$ for the sustainable or steady state yield function[4] as follows:

$$h = \sigma(x) = x - f^{-1}(x).$$

It is convenient to also introduce the sustainable or steady state mortality rate F_{lim} related to stock level x_{lim}

$$F_{\mathrm{lim}} = \frac{\sigma(x_{\mathsf{lim}})}{x_{\mathsf{lim}}}.$$

[4]In the sense that $f(x - \sigma(x)) = x$.

It gives the following proposition for the viability kernel where thresholds $x_{\lim}$, $F_{\lim}$ and F_{par} play crucial roles.

Proposition 1. *Assume f is continuously increasing and $\sigma(x)/x$ is decreasing. We obtain*

- *If $F_{\lim} < F_{par}$ then no viability occurs* $\text{Viab} = \emptyset$.
- *If $F_{par} \leq F_{\lim}$ then the viability kernel is* $\text{Viab} = [x_{\mathsf{lim}}, \infty[$.

This proposition emphasizes that the viability of quota management strategies based on ITQ depends on the current status of the stock through the floor threshold $x_{\lim}$ and the dynamics of the stock through mortality rate $F_{\lim}$. We also elaborate below in paragraphs 3.3, 3.4 and 3.5 the role played through mortality rate F_{par} by both the heterogeneity and the number of agents together with the guaranteed effort threshold.

Figure 1 shows how these two cases differ in the stock vs. mortality space (x, F). The socially induced constraint on the fishing mortality rate is represented by the horizontal straight line F_{par}. The economic constraint is represented by the increasing linear function $\alpha px - \beta$. The intersection of these two constraints gives the critical stock x_{lim}. The viability domain corresponds to the area which lies above the social constraint and below the economic constraint. We also represent the sustainable yield curve $\sigma(x)/x$. The shape of this curve refers to a population dynamics specified by a Beverton-Holt relation[5]. The case with no viability depicted in Figure 1a) results from the position of the participation constraint. The mortality rate required to ensure a positive effort for the least efficient user is too high, as compared to the sustainable mortality rate associated with the stock constraint. Since the intersection of the two constraints is above the sustainable yield curve, the dynamics of the resource will be strictly decreasing if the participation constraint is observed and finally the stock constraint $x_{\lim}$ will be violated. Case b) in Figure 1 represents the alternative case. An efficient trading allowing for the participation of all the users is possible despite their heterogeneity. In this case, the viability domain allows increasing or decreasing stock dynamics depending on whether the system is above or below the sustainable yield curve.

[5] With a logistic relation, the equilibrium sustainable yield curve is linear.

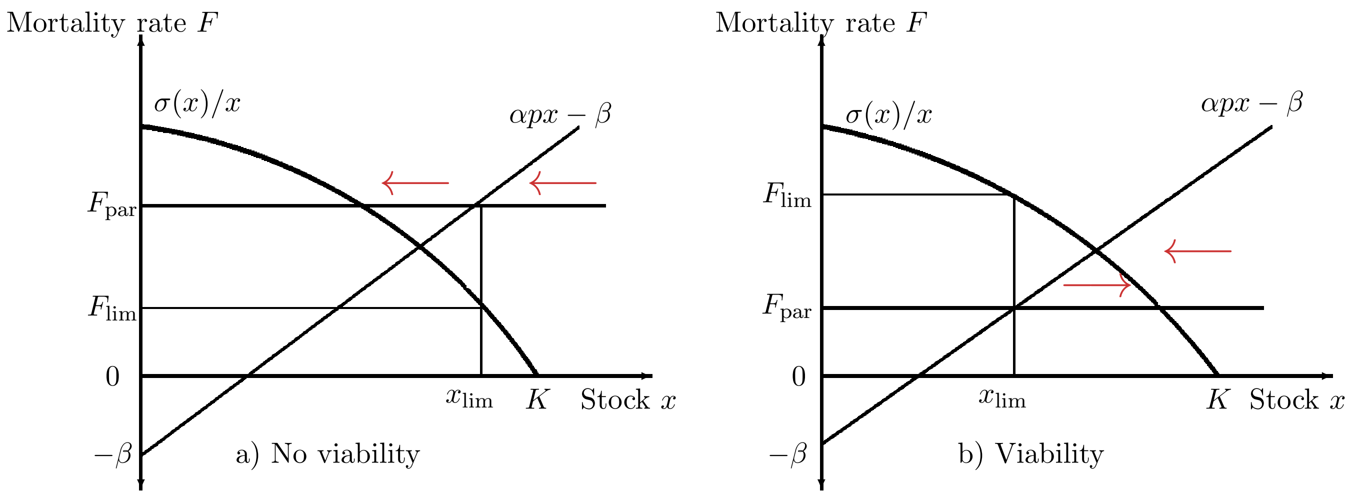

Figure 1: Two contrasted cases for viability: In case a) when $F_{\mathrm{lim}} < F_{\mathrm{par}}$, no viability occurs and the viability kernel $\mathrm{Viab} = \emptyset$ is empty. In case b) when $F_{\mathrm{lim}} \geq F_{\mathrm{par}}$, the viability kernel is $\mathrm{Viab} = [x_{\mathsf{lim}}, \infty[$.

3.2. Viable TACs

We derive the following proposition for the definition of viable TAC levels, which depend on the structure of harvesting costs, individual catchabilities of the agents, together with stock dynamics. The viable controls are selected in order to maintain the stock within the viability kernel using the dynamic programming structure explained in DeLara & Doyen (2008). In other words, the viable quotas $Q(t)$ are chosen to be admissible and to comply with the additional intertemporal condition $f(x(t) - Q(t)) \geq x_{\mathrm{lim}}$.

Proposition 2. *Assume f is continuously increasing and $\sigma(x)/x$ is decreasing. Assume that $F_{par} \leq F_{\mathrm{lim}}$. Then, for any stock x within the viability kernel* $\mathrm{Viab} = [x_{\mathsf{lim}}, \infty[$*, viable TAC controls lie in the interval*

$$Q(x) \in [F_{par}x, F_{pa}(x)x]$$

where precautionary mortality rate $F_{pa}(x)$ is defined as

$$F_{pa}(x) = \min\left(\alpha p x - \beta, 1 - \frac{f^{-1}(x_{\mathsf{lim}})}{x}\right).$$

The lower level $Q = F_{\mathrm{par}}x$ of viable TAC basically relies on participation constraint (14). The upper bound $F_{\mathrm{pa}}(x)x$ is related to the dynamic programming condition $f(x - Q) \geq x_{\mathrm{lim}}$ mixed with the economic constraint (10).

Figure 2 displays the viable TAC policies when the viability kernel is not empty. In the stock vs. mortality space (x, F), the second term of $F_{\text{pa}}(x)$ denoted by $F_+(x)$ can be rewritten as

$$F_+(x) = 1 - \frac{x_{\text{lim}}}{x}(1 - F_{\text{lim}})$$

with $F_{\text{lim}} < 1$. It can be shown that $F_+(x)$ is increasing and concave.[6] The viability quota domain corresponds to the area which lies above the social constraint and below the precautionary mortality rate.

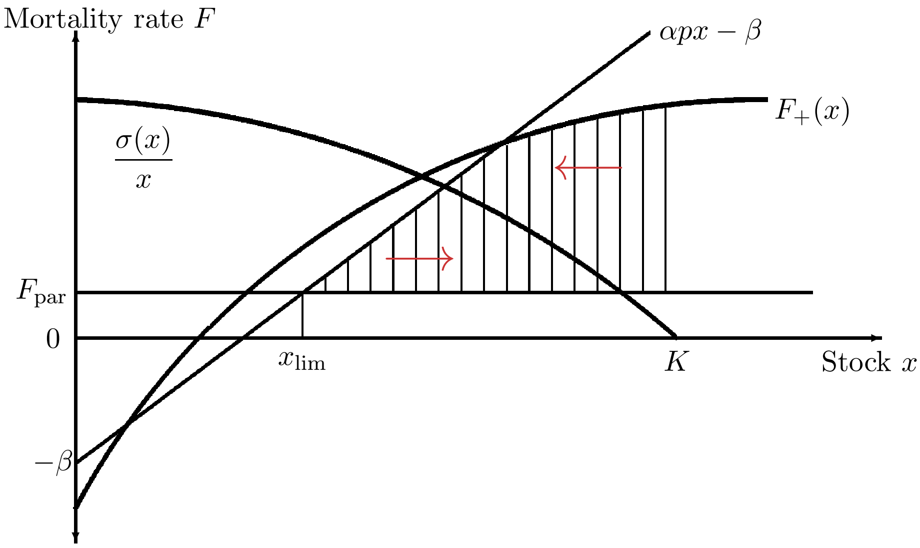

Figure 2: Feasible or viable mortalities $[F_{\text{par}}, F_{\text{pa}}(x)]$ (hatched) as a (multi)function of stock x. Stock has to lie within the viability kernel Viab and to be larger than x_{lim}.

It turns out that several TAC policies may exist, that allow distinct strategies and trade-offs between the biological aims of stock conservation and the economic aims of rent maximisation, while also respecting the social constraint. The set of TAC policies can be rewritten as

$$Q(x) = (\omega F_{\text{par}} x + (1 - \omega) F_{\text{pa}}(x))\, x$$

with $0 \leq \omega \leq 1$. High values of ω refer to an ecological conservation viewpoint since they favor the resource. Low values of ω promote current catches

[6] We have $F_+(x) < 0$ for $x \to 0$, $F_+(x) = F_{\text{lim}}$ for $x = x_{\text{lim}}$ and $F_+(x) \to 1$ for $x \to \infty$.

and rent. Mixed strategies can also be implemented. However the highest TAC given by $F_+(x)$ can only be implemented once a time since

$$x(t+1) = f\left(x(t)\left(1 - F_+(x)\right)\right) = f\left(x_{\text{lim}}\left(1 - F_{\text{lim}}\right)\right) = x_{\text{lim}}.$$

A comparison with usual MSY or MEY quotas is proposed in the example of section 4.

3.3. Heterogeneity of agents alters the viability

The role played by heterogeneity among the agents can be analysed via the efficiency parameter λ already defined in equation (12) by

$$\lambda = \max_i \frac{c_{1,i} + c_{2,i} E_{\text{lim}}}{q_i}.$$

The more the agents differ in efficiency terms (typically through usual open-access levels $\frac{c_{1,i}}{q_i}$), the more λ is high. Following from the characterization of the viability kernel in Proposition 1, we can also evaluate viability through the index:

$$V = F_{\text{lim}} - F_{\text{par}}.$$

Indeed, such a V has positive values whenever viability occurs as the viability kernel is not empty while V has negative values whenever there is an empty kernel. This viability index V depends on the heterogeneity parameter λ through the relation

$$V(\lambda) = p\lambda^{-1}\sigma(\lambda p^{-1}) - \alpha\lambda + \beta.$$

In fact, heterogeneity weakens the viability of ITQ system, in the following sense.

Proposition 3. *Assume f is continuously increasing and $\sigma(x)/x$ is decreasing and smooth. Then V is decreasing with respect to λ:*

$$\frac{d}{d\lambda} V(\lambda) \leq 0.$$

To prove this last statement, we compute the derivative of V with respect to λ. We obtain

$$\frac{d}{d\lambda} V(\lambda) = \frac{d}{dx}\frac{\sigma(x)}{x} p^{-1} - \alpha.$$

And note that the function $\sigma(x)/x$ is decreasing and α is positive or null.

3.4. Maximal guaranteed effort

The largest value for the guaranteed effort $E_{\lim}$ given a current state x is defined as follows:

$$E^*(x) = \max\left(E_{\lim} \geq 0 \mid x \in \text{Viab}\right).$$

As pointed out in DeLara & Doyen (2008); Martinet & Doyen (2007); Martinet (2010), this is strongly related to the maximin approach. Using the characterization of the viability kernel in Proposition 1, we obtain the following result involving the open access levels x_i^{oa} defined in (16).

Proposition 4. *Assume f is continuously increasing and $\sigma(x)/x$ is decreasing. Then*

$$E^*(x) = \begin{cases} 0 & \textit{if} \quad x \leq \max_i x_i^{\mathrm{oa}} \\ \min_i \dfrac{pq_i x - c_{1,i}}{c_{2,i}} & \textit{if} \quad \max_i x_i^{\mathrm{oa}} \leq x \leq V^{-1}(0) \\ \min_i \dfrac{pq_i V^{-1}(0) - c_{1,i}}{c_{2,i}} & \textit{if} \quad x \geq V^{-1}(0) \end{cases}$$

where the function V is defined by $V(x) = \sigma(x)x^{-1} - (\alpha p x - \beta)$.

The assertion is proved in section 6. Figure 3 displays the behavior of the maximin function $E^*(x)$. It is worth pointing out that a difficulty for viability occurs whenever such maximin effort $E^*(x)$ is zero. This can happen when the resource stock is lower than the largest open access level $x_i^{\mathrm{oa}} = \frac{c_{1,i}}{pq_i}$ among the agents. In other words, no guaranteed effort can be achieved if inefficiency characterizes the exploitation of the resource.

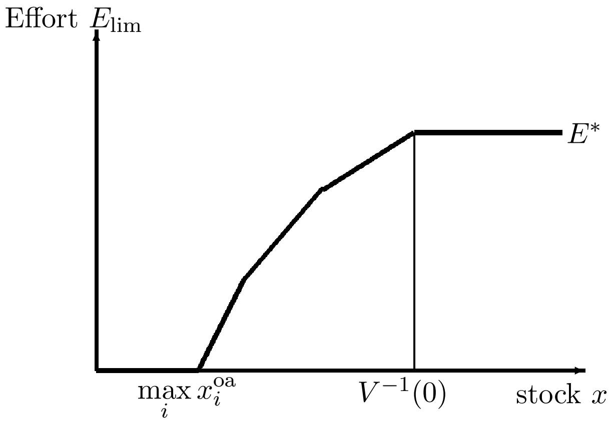

Figure 3: The maximin effort level $E^*(x)$ with respect to the stock x.

3.5. Number of active agents

The viability kernel is empty when $F_{\text{par}} > F_{\lim}$. This can occur when the desired guaranteed effort $E_{\lim}$ is too stringent regarding the maximin level $E^*(x)$ or when the maximin level $E^*(x)$ is zero. In these cases, the policy maker knows that it will not be feasible to respect the participation constraint for all agents and maintain the less efficient users active in the fishery, given the stock level x and the heterogeneity amongst users. His problem can be re-cast in terms of the maximal number of viable users denoted by $n^*(x)$ that the system could allow to remain active. This maximal number of viable agents is defined as follows

$$n^*(x) = \max\left(a \in \{0, \dots, n\} \;\middle|\; x \in \text{Viab}(a)\right)$$

where $\text{Viab}(a)$ means the viability kernel associated with $a \leq n$ agents supposed to be ranked according to

$$\frac{c_{1,1}}{q_1} \leq \frac{c_{1,2}}{q_2} \leq \dots \leq \frac{c_{1,a}}{q_a}.$$

Based on Proposition 1, we can characterize this maximal number of active fishers through the adaptation of critical thresholds $F_{\text{par}}(a)$, $x_{\lim}(a)$ and $F_{\lim}(a)$. They need to be defined as follows

$$\begin{cases} F_{\text{par}}(a) = \alpha(a)\lambda(a) - \beta(a) \\ x_{\mathsf{lim}}(a) = \dfrac{\lambda(a)}{p} \\ F_{\lim}(a) = \dfrac{\sigma(x_{\mathsf{lim}}(a))}{x_{\mathsf{lim}}(a)} \end{cases}$$

with

$$\alpha(a) = \sum_{i=1}^{a} \frac{q_i^2}{c_{2,i}}, \; \beta(a) = \sum_{i=1}^{a} \frac{c_{1,i} q_i}{c_{2,i}}, \; \lambda(a) = \max_{i=1,.,a} \frac{c_{1,i} + c_{2,i} E_{\mathrm{lim}}}{q_i}.$$

Based on this, we derive the following proposition.

Proposition 5. *Assume f is continuously increasing and $\sigma(x)/x$ is decreasing. Then*

$$n^*(x) = \max\left(a \leq n \,\middle|\, x_{\mathsf{lim}}(a) \leq x \text{ and } F_{par}(a) \leq F_{\mathsf{lim}}(a) \right).$$

Whenever $n^*(x)$ is strictly positive, it is feasible to ensure a positive effort for the $n^*(x)$ users through the TAC policies defined in Proposition 2. The set of TAC policies is defined as

$$Q^*(x) = \big(\omega F_{\mathrm{par}}(n^*(x))x + (1-\omega)F^*_{\mathrm{pa}}(x)\big)\, x$$

where upper viable or precautionary quota $F^*_{\mathrm{pa}}(x)$ correspond to:

$$F^*_{\mathrm{pa}}(x) = \min\left(\alpha(n^*(x))px - \beta(n^*(x)), 1 - \frac{f^{-1}(x_{\mathsf{lim}}(n^*(x)))}{x} \right).$$

4. Numerical Example

To illustrate the analytical results, we present a model of the nephrops fishery in the Bay of Biscay and data depicted in Martinet *et al.* (2007)[7]. The population dynamics is specified as a Beverton-Holt relation for the biomass:

$$f(x) = \frac{Rx}{1+Sx}$$

[7] We use the model parameter values estimated by Martinet *et al.* (2007) to define our numerical example, with adaptations to allow for the specific aspects of our analysis to be represented. In particular, we modify the definition of costs in the vessel profit function to allow for a quadratic cost function, and we assume a pattern of heterogeneity in costs across vessels. Hence, this example should be considered as illustrative only, and the conclusions reached should not be taken to be directly applicable to the actual fishery.

where we set $R = 1.78$ and $S = 253.10^{-7}$ to warrant a positive equilibrium carrying capacity $K = 30800$ tons defined as $K = (R-1)/S$. The equilibrium function σ is:

$$H = \sigma(x) = x\left(1 + \frac{1}{Sx - R}\right).$$

For $0 < x < K$, the function $\frac{\sigma(x)}{x}$ is decreasing, positive and lower than unity as required. The maximum sustainable biomass x_{MSY} and harvest H_{MSY} are given by:

$$x_{\mathrm{MSY}} = \frac{R + \sqrt{R}}{S}, H_{\mathrm{MSY}} = \frac{(R + \sqrt{R})^2}{S}.$$

We obtain $x_{\mathrm{MSY}} \approx 17604$ tons and $H_{\mathrm{MSY}} \approx 4409$ tons. The price of the resource is set at $p = 8500$ euros per ton. The initial stock of the resource estimated at year $t_0 = 2003$ is set at $x_0 = 18600$ tons and the potential number of agents (vessels) involved in the fishery is $n = 235$. For the cost structure, we consider the following quadratic function inspired by (Clark, 2006)

$$C_i(E) = 70000 + c_{1,i}E + 0.1E^2$$

where effort stands for days at sea per year. We introduce heterogeneity on vessels through the definition of unit linear costs $c_{1,i}$ as a uniform random variable over the interval $[377*(1-\delta), 377*(1+\delta)]$ for the 235 vessels. The dispersion rate is set to $\delta = 10\%$. The catchability coefficient is assumed equal to $q_i = 72.10^{-7}$ for all vessels.

We first compute the maximal guaranteed viable effort $E^*(x_0) \approx 128$ days at sea as defined in Proposition 4. Viable trajectories from t_0 are plotted for this case in Figure 4. All the 235 vessels participate in the catches and the quota market. The viability kernel is defined for the values of the stock which are above the critical stock level $x_{\mathsf{lim}}(n) \approx 6936 < x_0$. At each time step, the manager can choose any value of the parameter ω in $[0,1]$ to set a viable TAC $Q(x) = (\omega F_{\mathrm{par}} x + (1-\omega)F_{\mathrm{pa}}(x))\, x$. Note that the stock $x(t)$ remains at low levels close to $x_{\mathsf{lim}}(a) \approx 6936$ compared to MSY or MEY reference points. Similarly the quota price $m(t)$ is trapped into low values.

However such a guaranteed effort $E^*(x_0) \approx 128$ is lower than the effort $E(t_0) = 163$ in t_0. If the regulating agency aims at ensuring such an effort $E_{\lim} = 163$, Proposition 5 suggests to compute the maximal number of viable vessels which is strictly lower than $n = 235$. It turns out that $n^*(x_0) \approx 214$. To illustrate our results, we reduce the system to $a = 150 < n^*(x_0)$ viable licensed users. The quota policy is only implemented for these viable users. Under this new scenario, the viability stock threshold $x_{\mathsf{lim}}(a) = 6,755 < x_0$ is reduced. This generates the viable trajectories depicted in Figure 5. Compared to the previous case, higher levels of bio-economic performance are observed. In particular the mean stock and catches reach values close to MSY (red) or MEY (blue) reference points.

5. Conclusion

This paper addresses the problem of the sustainable management of a renewable resource based on the allocation of a Total Allowable Catch (TAC) through individual and transferable quotas (ITQs), when heterogeneous agents choose their effort levels and quotas to maximize their net profits. Assuming that regulation of the fishery is achieved through the selection of TAC policy, we determine the feasibility conditions under which a manager can simultaneously achieve ecological, economic and social objectives through time. We use a dynamic bio-economic model that shares some common features with the theoretical literature. As in Heaps (2003), we examine the determination of effort levels, the price of quotas and the number of agents in a regulated fishery. However our model gives new results. In particular, while the fact that ITQs can ensure the joint economic and ecological sustainability of a fishery has been known theoretically, and documented by empirical evidence (Squires *et al.*, 1994; Newell *et al.*, 2005; Costello *et al*, 2008), our model also suggests that social (participation) goals may potentially be achieved under these management regimes.

Results show that the ITQ management system is viable in a triple bottom line sense only under very specific conditions. This emphasizes that ITQs are not a panacea and should be designed carefully as suggested by Sumaila (2010). Firstly, maintaining levels of participation in an ITQ managed fishery implies conditions on the structure of fishing costs and catchability of the agents, together with population dynamics. In particular we show that pursuing both social and economic efficiency objectives will be relatively easier where there is a relative homogeneity of resource users, for a given resource status. In such a case, it is possible to determine the maximin feasible effort levels for a given set of participants. Secondly, our analysis also emphasizes the fact that the social constraint entails a stock maintenance constraint which may go beyond levels of protection that would be warranted by strict economic efficiency objectives, leading to the existence of trade-offs between the two objectives. This is because if the resource decreases below a critical level, it will not be possible to ensure that all agents remain active. Where maintaining the initial set of agents active is not feasible, because of too much heterogeneity between agents or of an initial stock which is too low, we define and characterize what the maximal number of active agents can be. In contexts where excess capacity in the fishery exists, such information allows to quantify the decrease in fleet size which should occur under ITQs, as mentioned for instance in Kompas & Che (2005) and in Pinkerton & Edwards (2009). Based on this maximal number of active agents, we identify alternative viable TAC strategies and assess the trade-offs between the different dimensions of the triple bottom line for fisheries management.

Overall, the results point to the necessity of better characterizing the bio-economic status of fisheries, prior to the introduction of access regulations based on the allocation of tradeable catch privileges. This status will determine the potential conflicts between management objectives which the approach may encounter, and in the end affect the acceptability and practical feasibility of the approach itself.

6. Proofs

We basically refer to methods and results detailed in StPierre (1994); DeLara & Doyen (2008); Doyen and De Lara (2010) for discrete time models under constraints.

6.1. Proof of proposition 1

We first define the viability kernel $\mathrm{Viab}(t,T)$ at time t for a finite horizon T through backward induction inspired by dynamic programming. First, at the terminal date T, we set

$$\mathrm{Viab}(T,T) = \{x \mid x \geq x_{\mathrm{lim}}\} . \tag{18}$$

For any time $t = 0, 1, .., T-1$, we compute the viability kernel $\mathrm{Viab}(t,T)$ at time t from the viability kernel $\mathrm{Viab}(t+1,T)$ at time $t+1$ as follows:

$$\mathrm{Viab}(t-1,T) = \{x \geq x_{\mathsf{lim}}, \exists Q \mid f(x-Q) \in \mathrm{Viab}(t,T)\} . \tag{19}$$

To compute the viability kernel Viab for an infinite horizon $T = +\infty$ as in the definition (17), we write

$$\mathrm{Viab} = \bigcap_T \mathrm{Viab}(0,T). \tag{20}$$

We first claim that:

Lemma 1.

$$\mathrm{Viab}(t,T) = \begin{cases} [x_{\mathsf{lim}}, +\infty[& if \quad F_{par} \leq F_{\mathrm{lim}} \\ [x_{\mathsf{lim}}(T-t), +\infty[& if \quad F_{par} > F_{\mathrm{lim}} \end{cases}$$

where $x_{\mathsf{lim}}(t)$ is defined by induction through

$$x_{\mathsf{lim}}(t+1) = \frac{f^{-1}(x_{\mathsf{lim}}(t))}{1-F_{par}}, \; x_{\mathsf{lim}}(0) = x_{\mathsf{lim}}. \tag{21}$$

The proof of lemma 1 is provided later on in subsection 6.2. Assuming for a while that it holds true, we deduce the shape of the viability kernel Viab defined in (20) for an infinite horizon $T = +\infty$.

In the first case with $F_{\mathrm{par}} \leq F_{\mathrm{lim}}$, we obviously conclude since

$$\mathrm{Viab} = \bigcap_T \mathrm{Viab}(0,T) = \bigcap_T [x_{\mathsf{lim}}, +\infty[= [x_{\mathsf{lim}}, +\infty[.$$

In the second case with $F_{\rm par} > F_{\rm lim}$, we conclude that

$$\mathrm{Viab} = \bigcap_T \mathrm{Viab}(0,T) = \bigcap_T [x_{\mathsf{lim}}(T), +\infty[= \left[\sup_T x_{\mathsf{lim}}(T), +\infty\right[= \emptyset$$

since

$$\sup_{T\to+\infty} x_{\mathsf{lim}}(T) = \lim_{T\to+\infty} x_{\mathsf{lim}}(T) = +\infty.$$

Let us prove this last assertion. First, in that case, we note that the sequence $x_{\mathsf{lim}}(.)$ is increasing and thus $x_{\mathsf{lim}}(t) \geq x_{\mathsf{lim}}$ as detailed in lemma 1. Second, we claim that for any time t we have

$$\frac{x_{\mathsf{lim}}(t+1)}{x_{\mathsf{lim}}(t)} \geq 1+\varepsilon$$

where $\varepsilon = \frac{F_{\rm par}-F_{\rm lim}}{1-F_{\rm par}} > 0$. Indeed, from the assumption that $\frac{\sigma(x)}{x}$ is a decreasing function, we deduce that the function $\frac{f^{-1}(x)}{x}$ is increasing and we obtain

$$\frac{x_{\mathsf{lim}}(t+1)}{x_{\mathsf{lim}}(t)} = \frac{f^{-1}\left(x_{\mathsf{lim}}(t)\right)}{x_{\mathsf{lim}}(t)(1-F_{\rm par})} \geq \frac{1}{1-F_{\rm par}}\frac{f^{-1}\left(x_{\mathsf{lim}}\right)}{x_{\mathsf{lim}}} = \frac{1-F_{\rm lim}}{1-F_{\rm par}} = 1+\varepsilon.$$

Finally we induce that

$$x_{\mathsf{lim}}(t) = x_{\mathsf{lim}}(1+\varepsilon)^t$$

and we conclude.

6.2. Proof of lemma 1:

We use a backward induction. First the assertion at time T is straightforward from the very definition of (18) and the fact that

$$x_{\mathsf{lim}}(0) = x_{\mathsf{lim}}.$$

Now let us assume that the lemma holds true at time $t+1$. Consider now any state $x \in \mathrm{Viab}(t,T)$. From the dynamic programming structure of the viability kernel $\mathrm{Viab}(t,T)$ depicted in (19), we deduce that $x \geq x_{\mathsf{lim}}$ along with the existence of an admissible quota Q such that

$$f(x-Q) \in \mathrm{Viab}(t+1,T).$$

Such catch Q is admissible if it satisfies the constraints

$$\alpha p x - \beta \geq \frac{Q}{x} \geq F_{\rm par} \text{ and } f\left(x-Q\right) \geq x_{\mathsf{lim}}(T-(t+1))$$

which yields

$$x - f^{-1}\left(x_{\mathsf{lim}}(T-t-1)\right) \geq Q \geq F_{par}x.$$

This implies

$$x \geq \frac{f^{-1}\left(x_{\mathsf{lim}}(T-t-1)\right)}{1-F_{\mathrm{par}}}.$$

By virtue of the sequence (21), this is equivalent to

$$x \geq x_{\mathsf{lim}}(T-t).$$

To sum up, we obtain $x \geq \max\left(x_{\mathsf{lim}}(T-t), x_{\mathrm{lim}}\right)$ and

$$\mathrm{Viab}(t,T) = \left[\max\left(x_{\mathsf{lim}}(T-t), x_{\mathrm{lim}}\right), +\infty\right[.$$

We now distinguish the two cases:

Case $F_{\mathbf{par}} \leq F_{\mathrm{lim}}$. Let us prove recursively that $\max\left(x_{\mathsf{lim}}(t), x_{\mathsf{lim}}\right) = x_{\mathsf{lim}}$. This clearly occurs at time $t = 0$. Now assume the condition holds at time t namely that $x_{\mathsf{lim}}(t) \leq x_{\mathsf{lim}}$. Then as f and f^{-1} are increasing functions, we claim that

$$F_{\mathrm{par}} \leq F_{\mathrm{lim}} \Longrightarrow F_{\mathrm{par}} \leq 1 - \frac{f^{-1}\left(x_{\mathsf{lim}}\right)}{x_{\mathsf{lim}}} \Longrightarrow F_{\mathrm{par}} \leq 1 - \frac{f^{-1}\left(x_{\mathsf{lim}}(t)\right)}{x_{\mathsf{lim}}}.$$

In other words, we have

$$x_{\mathsf{lim}} \geq \frac{f^{-1}\left(x_{\mathsf{lim}}(t)\right)}{1-F_{\mathrm{par}}} = x_{\mathsf{lim}}(t+1)$$

and we conclude that $\mathrm{Viab}(t,T) = [x_{\mathrm{lim}}, +\infty[$.

Case $F_{\mathrm{lim}} < F_{\mathbf{par}}$. Symmetric inductive reasonings yield that $\max\left(x_{\mathsf{lim}}(t), x_{\mathsf{lim}}\right) = x_{\mathsf{lim}}(t)$ in that case and we conclude similarly that $\mathrm{Viab}(t,T) = [x_{\mathrm{lim}}(T-t), +\infty[$.

6.3. Proof of proposition 4

To prove Proposition 4, we first note that the inverse V^{-1} of function V exists because V is continuous and decreasing as proved in section 3.3 with $V_x < 0$. Now, using Proposition 1 and the definition of F_{lim} and F_{par}, we write

$$\begin{aligned} E^*(x) &= \max\left(E_{\mathrm{lim}} \mid x \geq x_{\mathrm{lim}},\ F_{\mathrm{lim}} \geq F_{\mathrm{par}}\right) \\ &= \max\left(E_{\mathrm{lim}} \mid x \geq x_{\mathrm{lim}},\ V^{-1}(0) \geq x_{\mathrm{lim}}\right). \end{aligned}$$

When $V(x) \geq 0$ or equivalently $x \leq V^{-1}(0)$, then

$$E^*(x) = \max\left(E_{\text{lim}} \mid x \geq x_{\text{lim}}\right).$$

Then we use the definition of $x_{\text{lim}} = \max_i \frac{c_{1,i}+c_{2,i}E_{\text{lim}}}{pq_i}$ to derive the condition

$$E_{\text{lim}} \leq \min_i \frac{pq_i x - c_{1,i}}{c_{2,i}}.$$

Consequently, $E^*(x) = \max\left(E_{\text{lim}} \geq 0 \mid E_{\text{lim}} \leq \min_i \frac{pq_i x - c_{1,i}}{c_{2,i}}\right)$. In the first case where $x \leq \max_i x_i^{\text{oa}}$, we obtain that $E^*(x) = 0$ while in the second case, we have $E^*(x) = \min_i \frac{pq_i x - c_{1,i}}{c_{2,i}}$. We follow similar reasoning for the case where $V(x) < 0$.

Acknowledgement 1. *This work was supported by the ANR ADHOC project.*

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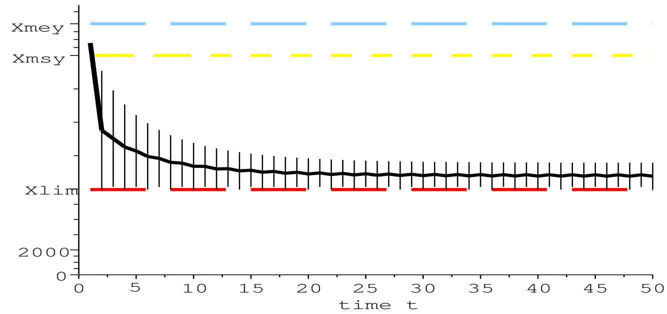
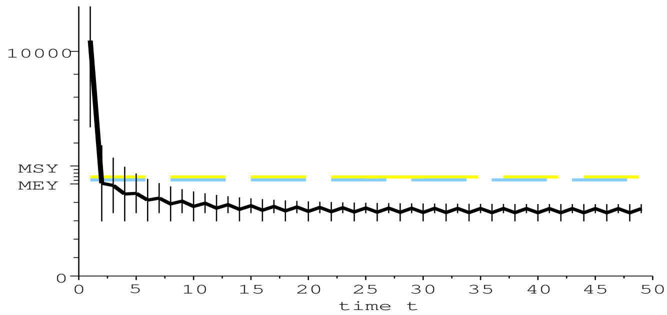
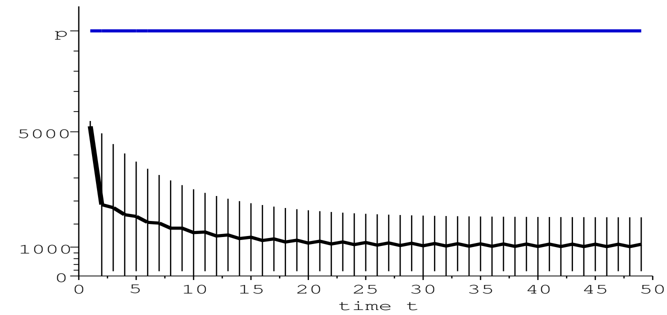


(a) Stock $x(t)$ (tons)

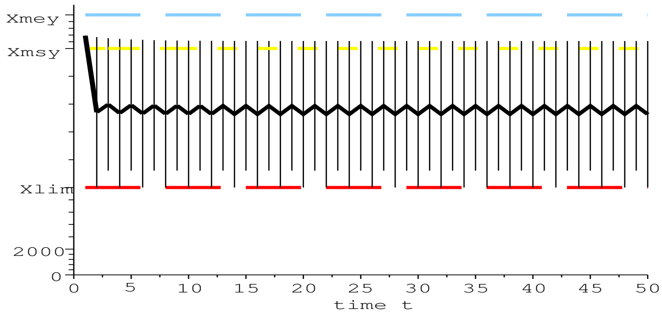


(b) Quotas $Q(t)$ (tons)

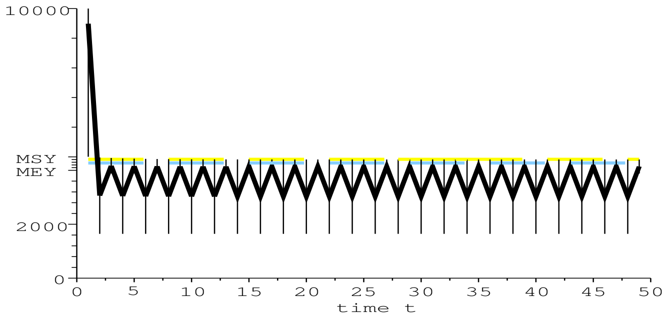


(c) Quota price $m(t)$ (euros/tons)

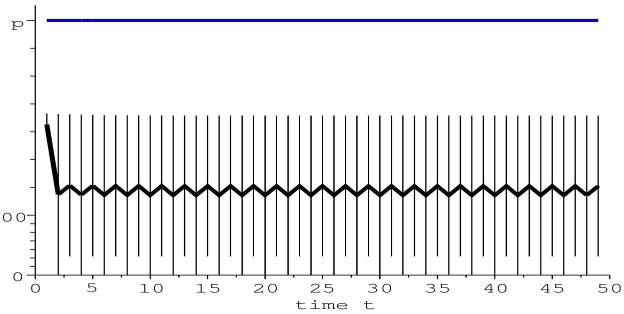
Figure 4: Viable trajectories (mean and dispersion) in black for $n = 235$ agents with initial stock $x_0 = 18600$ (tons) and maximin threshold effort $E_{\text{lim}} = E^*(x_0) = 117$ (days at sea). After a declining transition, the stock remains close to the viable threshold $x_{\mathsf{lim}}(n) \approx 6850$ in red. MSY and MEY reference points are in yellow and blue.



(a) Stock $x(t)$ (tons)



(b) Quotas $Q(t)$ (tons)



(c) Quota price $m(t)$ (euros/tons)

Figure 5: Viable trajectories (mean and dispersion) in black for $n = 150 < n^*(x_0) = 214$ agents with initial stock $x_0 = 18600$ (tons) and maximin threshold effort $E_{\text{lim}} = 163$ (days at sea). Note that, in this case, the mean stock and the total catches increase compared to the $n = 235$ scenario. In particular the mean stock and total catches reach values closer to MSY (yellow) or MEY (blue) reference points.

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