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Journal of Environmental Economics and Management ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at SciVerse ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

The triple bottom line: Meeting ecological, economic and social goals with individual transferable quotas

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ARTICLE INFO

Article history:
Received 20 January 2011

Keywords:
Renewable resource
Sustainability
Total allowable catch
Individual and transferable quotas
Maximin
Feasibility set

ABSTRACT

This paper deals with the sustainable management of a renewable resource based on individual and transferable quotas (ITQs) when agents differ in terms of harvesting costs or catch capability. In a dynamic bio-economic model, we determine the feasibility conditions under which a fishery manager can achieve sustainability objectives which simultaneously account for stock conservation, economic efficiency and maintenance of fishing activity for the agents along time. We show how the viability of quota management strategies based on ITQ depends on the degree of heterogeneity of users in the fishery, the current status and the dynamics of the stock together with the selection of TAC schedules. In particular for a given stock, we compute the *maximin* effort for a given set of agents and we derive the maximal number of active agents for a given guaranteed effort. An application to the nephrops fishery in the Bay of Biscay illustrates the results.

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1. Introduction

Numerous renewable resources are under extreme pressure worldwide, particularly in marine fisheries [26]. A key reason for this is the common pool status which creates incentives for fishing firms to invest in fishing capacity beyond collectively efficient levels [27,36,37]. This has led to the recognition that access regulations are important in guiding resource use on sustainable paths that respect the ecological, economic and social goals of the triple bottom line [24].

Restricting access to fisheries and allocating shares of a Total Allowable Catch (TAC) as secure harvesting privileges to fishers has been proposed as a promising way forward in this domain [9,28,7]. 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 [10,29]. Recent reviews of the experience with ITQs in fisheries show that they are increasingly being adopted, and that this has been associated with improved status of fish stocks and levels of catches (see e.g. [48,14,8,23]).

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doi:10.1016/j.jeem.2012.01.001

Please cite this article as: J.-C. Péreau, et al., The triple bottom line: Meeting ecological, economic and social goals with individual transferable quotas, Journal of Environmental Economics and Management (2012), doi:10.1016/j.jeem.2012.01.001

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 [38]. Indeed, an immediate consequence of allowing individual quotas to be transferred has in many cases been a rapid reduction in fishing capacity, as measured by, the number of registered vessels, or the number of active fishers and firms. Although this is an impact that could be expected, and to some extent desired, it has turned out to be one of the key points of debate on the opportunity and effectiveness of introducing ITQs as a management instrument in fisheries [49]. This is due in particular to the resulting concentration of fishing privileges in the hands of smaller groups, and to the reduced nominal size of fishing activities in coastal areas [13,48,32]. The social consequences of these reductions have in some cases been considered important enough that they may outweigh the expected ecological and economic benefits of the regulations, leading to question their acceptability and feasibility, as was illustrated during the EU consultation on "rights-based" fisheries management that preceded the revision of the Common Fisheries Policy [1].

In this paper, we aim to address the tradeoffs that arise between conservation and the drive for economic efficiency and social objectives in an ITQ managed fishery. We develop a dynamic bio-economic model of a fishery composed of heterogeneous participants and including an explicit representation of the quota market. There have been various approaches to modeling ITQs in fisheries, ranging from analytical models [5,35,6,33,11], linear programming approaches [39], through to models that use numerical simulation [21,30,31,41]. Despite the importance granted to social considerations in debates on ITQs, these have only rarely been explicitly included as an objective or a constraint in bio-economic models of fisheries. Heaps [35] 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. [6] analyzed the distributional issues of the ITQ system and showed that it can improve the welfare of some agents (the fishing captains and the consumers) at the expense of other agents (the input suppliers). Fulton et al. [25] have also drawn attention to the role of social networks in the operation of fisheries quota markets. However, little work has been done on the possible interactions between the social, economic and biological objectives which a policy maker may pursue with ITQs in a dynamic setting.

The analysis of our bioeconomic model relies on the weak invariance [12] or viable control method [2]. This approach focuses on identifying inter-temporal feasible paths within a set of desirable objectives or biological, social and economic constraints [4,22,16,3,46]. This framework has been applied to renewable resources management and especially to the regulation of fisheries (see, e.g. [4,45,17,19]), as well as to broader (eco)-system dynamics [15,20]. Our approach departs from these previous studies in that it explicitly represents heterogeneous operators and considers a set of controls that includes total fishing output, as well as a social objective which is expressed in terms of maintaining a level of activity in the fishery. While such a social objective was considered in Martinet et al. [45], it was with a focus on how it could effect the rate at which a fishery may recover from an initial state of crisis, using input-controls. Moreover, none of the existing applications of the viability method to fisheries to date have included an explicit representation of a quota market.

The major contribution of this paper is to show that the ITQ management system is viable in a triple bottom line sense only under very specific conditions. In particular, it is pointed out how the success of such a management depends on the degree of heterogeneity of agents operating in the fishery, the current status and the dynamics of the stock together with the design of TAC.

The paper is structured as follows. Section 2 is devoted to the description of the dynamic bio-economic model and the ecological, economic and social objectives which a manager may wish to observe. Section 3 characterizes the feasible stock states and quota policies and examines the role of heterogeneity between users. Then the maximum number of active fishers and the maximum guaranteed fishing effort are computed. 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) $x(t) \in \mathbb{R}$ at time t. If the amount removed $Q(t)$ is caught at the beginning of each time step, the dynamics of the exploited resource $x(\cdot)$ 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

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

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

$$Q(t) = \sum_{i=1}^{n} Q_i^-(t), \tag{3}$$

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 quota can freely be traded on a lease market and that inter-temporal trade of quota is not allowed.[1] The demand for quota is derived as the sum of the amount of harvest of the n agents

$$H(t) = \sum_{i=1}^{n} H_i(t). \tag{4}$$

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

$$\pi_i(E_i(t),x(t)) = pH_i(t) - C_i(E_i(t)) - m(t)(H_i(t) - Q_i^-(t)). \tag{5}$$

The harvest function and the quadratic cost function inspired by Clark [11, p. 163] are given by

$$H_i(t) = q_i E_i(t) x(t), \tag{6}$$

$$C_i(E_i) = c_{0,i} + c_{1,i}E_i + \frac{c_{2,i}}{2}E_i^2, \tag{7}$$

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

$$\max_{E_i \geq 0} \pi_i(E_i, x(t)). \tag{8}$$

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

$$E_i^*(t) = \frac{1}{c_{2,i}}((p - m(t))q_i x(t) - c_{1,i}), \tag{9}$$

and the associated optimal amount of harvest

$$H_i^*(t) = q_i E_i^*(t) x(t) = \frac{1}{c_{2,i}}((p - m(t))q_i x(t) - c_{1,i}) q_i x(t). \tag{10}$$

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

$$H^*(t) = \sum_{i=1}^{n} H_i^*(t) = x(t)\left[(p - m(t))x(t)\sum_{i=1}^{n}\frac{q_i^2}{c_{2,i}} - \sum_{i=1}^{n}\frac{c_{1,i}q_i}{c_{2,i}}\right]. \tag{11}$$

Setting

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

we obtain

$$H^*(t) = x(t)[(p - m(t))x(t)\alpha - \beta]. \tag{12}$$

From the quota market clearing condition

$$Q(t) = H^*(t), \tag{13}$$

we deduce the equilibrium rental price:

$$m^*(Q(t),x(t)) = p - \frac{\dfrac{Q(t)}{x(t)} + \beta}{x(t)\alpha}. \tag{14}$$

Thus, a rise in the quota supply implies a fall in the rental 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 quota. This yields an increase in the rental price and $m_x^*(Q,x) > 0$.

If a positive quota demand exists, then a unique rental price $m^*(Q(t),x(t))$ should exist such that $m^*(Q(t),x(t)) \in [0,p]$. The positivity condition on $m^*(Q(t),x(t))$ implies a state-control constraint

$$x(t)(px(t)\alpha - \beta) \geq Q(t). \tag{15}$$

In other words, application of the economic constraint entails a higher limit on the value of the TAC, which will depend on the biological state of the stock and the technical or economic parameters of the fishery.

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

Combining (15) with the scarcity constraint (2), we find that this yields the following stock constraint:

$$x(t) \geq \frac{\beta}{p\alpha}. \tag{16}$$

This result can be compared to the definition of the bionomic equilibrium stock level obtained by Clark (2006, p. 81) in the case of a homogeneous fishing fleet. In our case, a positive rental 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 objective

The model so far shows conditions which are needed to maximize economic returns to operators in the fishery from the quota they have been allocated. Managing for the triple bottom line requires that social and biological constraints also be considered. In an ITQ system where the initial situation is one of the excess capacity, one may observe a reduction in the number of participants leading to social disruption potentially beyond what is considered acceptable. To account for this, a social objective may thus be introduced to influence management decisions. Formally, we introduce a management objective of keeping a number of active fishers as

$$E_i^*(t) \geq E_{\lim} \quad \forall i = 1, \ldots, n, \tag{17}$$

where $E_{\lim} > 0$ stands for some agreed-upon guaranteed level of effort.

A direct interpretation of this social objective is to ensure that all n agents initially present remain active in the fishery. A more realistic interpretation would be that, provided the above economic constraint can be respected dynamically, the policy will seek to maintain some level of the social benefits associated with the maintenance of larger number of active operators, e.g. in terms of preserving certain lifestyles, and the regional community structures which rely on employment on board vessels as well as land-based upstream and downstream economic activities. By contrast, another economic strategy will be to allow the transition to the most profitable fishery and to compensate the "losers" using the increased rents that result. As suggested by Boyce [6], fishing captains support regulations that decrease their number only if those who exit get to share with those who remain. However, as argued in the introduction and above, there seems to be a large number of cases where the expected social impacts of such a transition are considered important enough that they can outweigh the expected ecological and economic benefits of ITQs, leading to the feasibility of their implementation being questioned.

Furthermore, the guaranteed effort objective (17) does not imply that fishers are being coerced into fishing which they would not voluntary do. This is just a management objective for selecting, if possible, TAC levels maintaining some positive level of sustainable fishing activity (effort) for every agent. In particular, this social constraint differs from maintaining the status quo and can potentially be lower than the current levels (see Section 3.4 for a formal analysis). For example, in the nephrops case study examined below in Section 4, this occurs where the maximum guaranteed individual effort is reduced by 25% with respect to the lowest level of individual effort under the status quo. Hence, this social objective may not be contradictory with rationalization underlying ITQs and the objective to reduce the global effort in the fishery when the status-quo level of effort in the fishery is unsustainable. In other words, by allowing a decrease of effort for some agents, the social constraint can be an alternative to the reduction of the capacity (number of vessels) in the whole fishery. It thus can be useful to anticipate and attempt to quantify the potential loss in fishing activities when adopting such ITQ systems. This corresponds to examining the implications of relaxing the effort constraint (17) when it is not feasible along time. Such issues are tackled through the notions of "*maximin*" effort or maximum number of active users introduced later on in Sections 3.4 and 3.5.

Moreover, the guaranteed effort constraint (17) provides an economic rationale for the voluntary participation of agents in the fishery. This occurs because such a constraint implies a positive gross or quasi-rent (revenue minus variable cost) $\tilde{\pi_i^*}$ associated with fishing for all the active fishers[2] in the following sense:

$$E_i^*(t) \geq E_{\lim} \Longrightarrow \tilde{\pi_i^*}(t) \geq \pi_{\lim}, \tag{18}$$

where the quasi rent $\tilde{\pi_i^*}$ is defined as follows: $\tilde{\pi_i^*} = \pi_i^* + c_{0,i}$. In other words, this implies that the decision to fish by operators may be based on private economic drivers derived from either using or selling their quota.[3]

[2] As the optimum of a quadratic function, $\tilde{\pi_i^*}$ simplifies to

$$\tilde{\pi_i^*} = \frac{c_{2,i}}{2}(E_i^*)^2 + mQ_i^-.$$

Consequently quasi rents for every agent are strictly positive with

$$\tilde{\pi_i^*} \geq \frac{c_{2,i}}{2}(E_{\lim})^2.$$

We can derive a lower guaranteed level of quasi-rent for every agent

$$\tilde{\pi_i^*} \geq \pi_{\lim} = \min_i \frac{c_{2,i}}{2}(E_{\lim})^2.$$

[3] However, implementing a guaranteed rent including fixed costs, as in [6], would be more demanding and technically difficult. This challenging and stimulating issue could be the core of future work to ensure a broader voluntary participation.

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The social objective (17) combined with the value of m^* given by (14) and the optimal effort E_i^* given by (9) leads to

$$\left(\frac{\frac{Q(t)}{x(t)}+\beta}{\alpha}\right)q_i - c_{1,i} \geq E_{\lim} c_{2,i} \quad \forall i=1,\ldots,n, \tag{19}$$

or equivalently

$$\frac{\frac{Q(t)}{x(t)}+\beta}{\alpha} \geq \max_i \frac{c_{1,i}+c_{2,i}E_{\lim}}{q_i} = \lambda. \tag{20}$$

Thus the activity goal 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

$$F_{\text{par}} = \alpha\lambda - \beta \geq 0, \tag{21}$$

the fishing mortality rate[4] which is associated with the social constraint, the previous constraint (20) reads

$$Q(t) \geq F_{\text{par}} x(t). \tag{22}$$

In other words, the social target (17) requires a minimum level for the TAC.

2.4. Stock constraint

We show that the existence of both economic and social constraints implies a stock constraint, defined as a minimum stock size required to maintain sustainable levels of catches and rent above viable levels. Based on Eqs. (15) and (22), the following inequality applies:

$$F_{\text{par}} \leq \frac{Q(t)}{x(t)} \leq \alpha p x(t) - \beta. \tag{23}$$

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

$$x(t) \geq \frac{F_{\text{par}}+\beta}{\alpha p} = \frac{\lambda}{p} = x_{\lim}. \tag{24}$$

Note that such a stock constraint (24) also implies that

$$x(t) > \max_i \frac{c_{1,i}}{pq_i} = \max_i x_i^{\text{oa}}, \tag{25}$$

where x_i^{oa} is related to the stock size at usual bionomic equilibrium[5] with open access for the user i. If we assume that the agents are ranked according to their first order efficiency level $c_{1,i}/pq_i$, the constraint (25) suggests that maintaining all fishers active in a fishery will require that the stock stays 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. This kernel is the feasibility set of initial stock sizes for which an acceptable regime of quotas exists and satisfies in time the constraints presented 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 in the fishery, for which the set of constraints can be satisfied.

3.1. Viability kernel

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

- the social objective (22): $Q(t) \geq F_{\text{par}} x(t)$,

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

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

[5] Assuming that the quadratic coefficient $c_{2,i}$ is close to zero.

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- the economic constraint (15): $Q(t) \leq (p\alpha x(t) - \beta)x(t)$,
- the stock constraint[6] (24): $x(t) \geq x_{\text{lim}}$.

In an infinite horizon context, the viability kernel for this decision problem can be defined as follows:

$$\text{Viab} = \left\{ x_0 \left| \begin{array}{l} \text{for any time horizon } T \in \mathbb{N} \\ \text{there exists TAC levels } Q(t) \text{ and resource states } x(t) \\ \text{starting from } x_0 \\ \text{satisfying all the constraints (15), (22), (24) and dynamics (1)} \\ \text{for time } t = 0, 1, \ldots, T \end{array} \right. \right\}. \tag{26}$$

As explained in [16,18], 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[7] as follows:

$$h = \sigma(x) = x - f^{-1}(x). \tag{27}$$

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

$$F_{\text{lim}} = \frac{\sigma(x_{\text{lim}})}{x_{\text{lim}}}. \tag{28}$$

This 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 $F_{\text{lim}} < F_{\text{par}}$ then no viability occurs* $\text{Viab} = \emptyset$.
- *If $F_{\text{par}} \leq F_{\text{lim}}$ then the viability kernel is* $\text{Viab} = [x_{\text{lim}}, \infty[$.[8]

This proposition emphasizes that the viability of TAC management strategies in an ITQ system where the social constraint applies depends on the current status of the stock as compared to the minimum stock threshold x_{lim} and on the effects of fishing on the stock as compared to the limit mortality rate F_{lim}. Two unsustainable cases can occur. A first critical situation corresponds to an empty viability kernel where the social objective as captured by mortality rate F_{par} is too demanding when compared to the fishing mortality rate F_{lim} associated with stock sustainability. A second non-viable situation occurs when the current status of the stock x_0 is smaller than the tipping stock state x_{lim} and consequently does not belong to the viability kernel.

Of interest is the fact that the assumption associated with the equilibrium curve $\sigma(x)/x$ could be satisfied by several usual population dynamics. Typically it holds true for the Beverton–Holt relation, the logistic function and the power function $f(x) = x^{\alpha}$, where $0 < \alpha < 1$.

Fig. 1 shows graphically how viable and non-viable cases differ in the stock versus fishing 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 $\sigma(x)/x$ in Fig. 1. The shape of this curve refers to a population dynamics specified by a Beverton–Holt relation. The case with no viability depicted in Fig. 1(a) results from the position of the social 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 social constraint is observed and finally the stock constraint x_{lim} will be violated. Case (b) in Fig. 1 represents the alternative case. 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.

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

[6] This last constraint is in fact a consequence of two previous ones.
[7] In the sense that $f(x - \sigma(x)) = x$.
[8] Or equivalently $[x_{\text{lim}}; \infty)$.

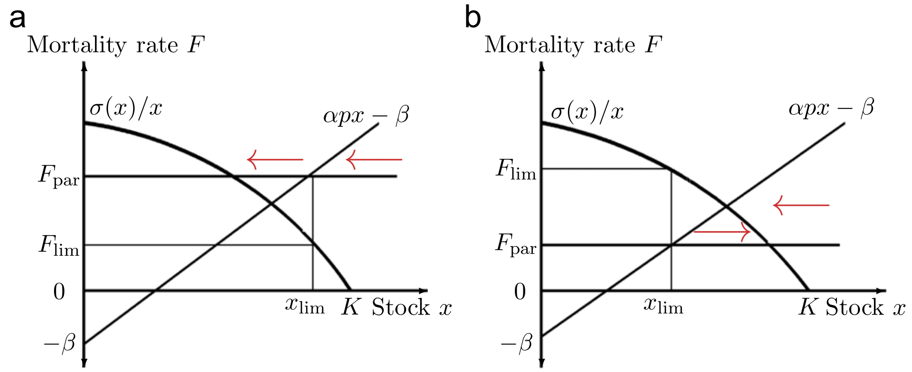

Fig. 1. Two contrasted cases for viability: in case (a) when $F_{\text{lim}} < F_{\text{par}}$, no viability occurs and the viability kernel $\text{Viab} = \emptyset$ is empty. In case (b) when $F_{\text{lim}} \geq F_{\text{par}}$, the viability kernel is $\text{Viab} = [x_{\text{lim}}, \infty[$.

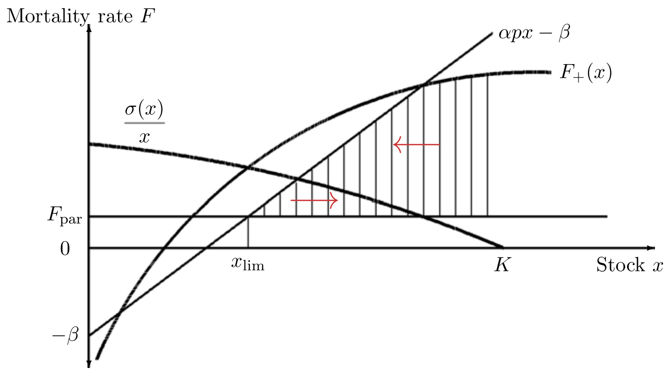

Fig. 2. Feasible or viable mortalities $[F_{\text{par}}, F_{\text{pa}}(x)]$ (hatched) as a (multi)function of stock x. Stock has to lie within the viability kernel Viab and to be larger than x_{lim}.

maintain the stock within the viability kernel using the dynamic programming structure explained in [16]. In other words, the viable quotas $Q(t)$ are chosen to be admissible and to comply with the additional intertemporal condition $f(x(t) - Q(t)) \geq x_{\text{lim}}$.

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

$$Q(x) \in [F_{\text{par}} x, F_{\text{pa}}(x) x], \tag{29}$$

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

$$F_{\text{pa}}(x) = \min\left(\alpha px - \beta, 1 - \frac{f^{-1}(x_{\text{lim}})}{x}\right). \tag{30}$$

The lower level $Q = F_{\text{par}} x$ of viable TAC stems directly from the social constraint (22). The upper bound $F_{\text{pa}}(x)x$ is related to the dynamic programming condition $f(x - Q) \geq x_{\text{lim}}$ mixed with the economic constraint (15).

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

$$F_{+}(x) = 1 - \frac{x_{\text{lim}}}{x}(1 - F_{\text{lim}}), \tag{31}$$

with $F_{\text{lim}} < 1$. It can be shown that $F_{+}(x)$ is increasing and concave.[9] The viability quota domain corresponds to the area which lies above the social constraint and below the precautionary mortality rate.

Several TAC policies may exist, that allow distinct strategies and trade-offs between the biological aims of stock conservation and the economic aim of maintaining individual levels of rent, while also respecting the social constraint. The

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

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set of TAC policies can be rewritten as

$$Q(x) = (\omega F_{\mathrm{par}} + (1-\omega)F_{\mathrm{pa}}(x))x, \tag{32}$$

with $0 \le \omega \le 1$. High values of ω refer to an ecological conservation viewpoint since they favor the resource. Low values of ω promote current catches and rent. Mixed strategies can also be implemented. However when the highest TAC given by $F_+(x)$ is implemented, the stock falls to the viable limit x_{lim}

$$x(t+1) = f(x(t)(1-F_+(x))) = f(x_{\mathrm{lim}}(1-F_{\mathrm{lim}})) = x_{\mathrm{lim}}. \tag{33}$$

The policy implications of ITQ system can be examined here by considering the extreme case where individual quotas are non-tradeable (IQ). This case is equivalent to set the rental price to zero and Eq. (9) gives the following individual optimal efforts:

$$E_i^*(t) = \frac{1}{c_{2,i}}(pq_i x(t) - c_{1,i}). \tag{34}$$

Hence the condition $E_i^*(t) \ge E_{\mathrm{lim}}$ also implies that

$$x(t) \ge \frac{c_{1,i}}{pq_i} + \frac{c_{2,i}E_{\mathrm{lim}}}{pq_i},$$

leading to the same minimum stock x_{lim} as in (24). Consequently, we can derive similar viability results as previously, based on the relative values of F_{lim} and F_{par}. A major difference with the case where quotas are transferable is that under an IQ system, the manager should design individual quotas supply $Q_i^-(t)$ so that it coincides with the optimal demand $H_i^*(t) = q_i E_i^*(t)x(t)$ of agents. Of course, such a centralized allocation mechanism would be very demanding in terms of information (on individual input and output prices, and technical efficiency). Moreover, as compared to the ITQ scenario, there would be a loss of flexibility in the setting of viable TAC policies because in the IQ case, there is a unique viable TAC $Q(t) = \sum_i q_i E_i^*(t)x(t)$. By contrast, in the ITQ system, we obtain a corridor $[F_{\mathrm{par}}x, F_{\mathrm{pa}}(x)x]$ of viable TAC policies as stressed by Proposition 2. Such flexibility provides greater opportunities for the design of adaptive management strategies.

3.3. *Heterogeneity of agents alters the viability*

The role played by heterogeneity among the agents can be analyzed via the efficiency (cost/catchability) parameter λ_i implicitly defined in Eq. (20) by

$$\lambda_i = \frac{c_{1,i} + c_{2,i}E_{\mathrm{lim}}}{q_i}. \tag{35}$$

In line with this, we define the following heterogeneity index:

$$\lambda = \max_i \lambda_i. \tag{36}$$

The more the agents differ, the higher the λ is. In other words, the "marginal agent" is the one that has the largest λ_i. We could typically assume the agents ranked by increasing value of their λ_i, the last (or n) agent being this "marginal agent".

Following from the characterization of the viability kernel in Proposition 1, we can also evaluate viability through the index:

$$V = F_{\mathrm{lim}} - F_{\mathrm{par}}. \tag{37}$$

From Proposition 1, V has positive values whenever the viability kernel Viab is not empty (and equal to $[x_{\mathrm{lim}}, +\infty[$). By contrast, V has negative values as soon as there is an empty kernel. This viability index V depends on the heterogeneity parameter λ through the relation

$$V(\lambda) = p\lambda^{-1}\sigma(\lambda p^{-1}) - \alpha\lambda + \beta, \tag{38}$$

which is derived from the fact that λ is equal to px_{lim}. In fact, heterogeneity weakens the viability of ITQ system, as we show below.

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

$$\frac{d}{d\lambda}V \le 0. \tag{39}$$

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

$$\frac{d}{d\lambda}V = \frac{d}{dx}\frac{\sigma(x)}{x}p^{-1} - \alpha, \tag{40}$$

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

The interpretation of Proposition 3 is that, given the social constraint, greater heterogeneity in the fishery reduces the viability kernel. If some operators have cost/catchability ratios λ_i that are too large, this will entail a stock constraint x_{lim} which will be too stringent as compared to current stock x_0. Alternatively, heterogeneity can also yield a situation where activity level F_{par} is too large as compared to F_{lim}, thus making the viability kernel collapse.

3.4. Maximal guaranteed effort

Given a current state x, the largest viable value for guaranteed effort E_{lim} is defined as follows:

$$E^*(x) = \max(E_{\text{lim}} \geq 0 | x \in \text{Viab}). \tag{41}$$

As pointed out in [44,16,46], 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 (25).

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

$$E^*(x) = \begin{cases} 0 & \text{if } x \leq \max_i x_i^{\text{oa}}, \\ \min_i \dfrac{pq_i x - c_{1,i}}{c_{2,i}} & \text{if } \max_i x_i^{\text{oa}} \leq x \leq V^{-1}(0), \\ \min_i \dfrac{pq_i V^{-1}(0) - c_{1,i}}{c_{2,i}} & \text{if } x \geq V^{-1}(0), \end{cases} \tag{42}$$

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

The proposition is proved in Section 6. Fig. 3 displays the behavior of the *maximin* function $E^*(x)$. Comparing this with current efforts $E_i(t_0)$ is informative as regards the sustainability of status quo. Two contrasted cases can be distinguished, depending on whether effort is larger than the *maximin* or not.

- In the case where $\max_i E_i(t_0) \leq E^*(x_0)$, the status quo strategy is viable because if $E^*(x_0) > 0$ is possible then lower effort through $\min_i E_i(t_0)$ can also be guaranteed.
- In the case where $\max_i E_i(t_0) > E^*(x_0)$, the status quo strategy is not viable at least for some agents. In other words, a reduction of the current effort of these agents would be necessary to allow viable management strategies using an ITQ system.

Lack of viability also occurs whenever such *maximin* effort $E^*(x)$ is zero. This can happen when the resource stock is lower than the largest open access stock level $x_i^{\text{oa}} = c_{1,i}/pq_i$ among the agents.

3.5. Number of active agents

The viability kernel is empty when $F_{\text{par}} > F_{\text{lim}}$. 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 social constraint for all agents and maintain the less efficient users active in the fishery, given the stock level x and the heterogeneity among users. The problem can then be re-cast in terms of the maximal number of

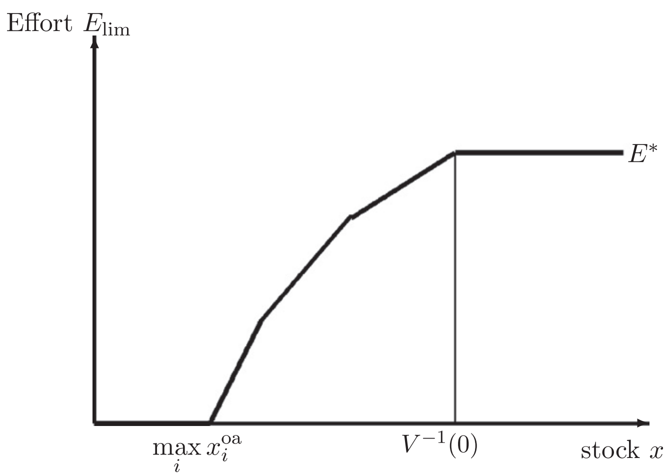

Fig. 3. The *maximin* effort level $E^*(x)$ with respect to the stock x.

viable users that the system could allow to remain active. This maximal number of viable agents denoted by $n^*(x)$ can defined as follows:

$$n^*(x) = \max(a \in \{0, \ldots, n\} | x \in \text{Viab}(a)), \tag{43}$$

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

$$\frac{c_{1,1}}{q_1} \le \frac{c_{1,2}}{q_2} \le \cdots \le \frac{c_{1,a}}{q_a}. \tag{44}$$

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:

$$\begin{cases} F_{\text{par}}(a) = \alpha(a)\lambda(a) - \beta(a), \\ x_{\lim}(a) = \dfrac{\lambda(a)}{p}, \\ F_{\lim}(a) = \dfrac{\sigma(x_{\lim}(a))}{x_{\lim}(a)}, \end{cases} \tag{45}$$

with

$$\alpha(a) = \sum_{i=1}^{a} \frac{q_i^2}{c_{2,i}}, \quad \beta(a) = \sum_{i=1}^{a} \frac{c_{1,i} q_i}{c_{2,i}}, \quad \lambda(a) = \max_{i=1,\ldots,a} \frac{c_{1,i} + c_{2,i} E_{\lim}}{q_i}. \tag{46}$$

Based on this, we derive the following proposition.

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

$$n^*(x) = \max(a \le n | x_{\lim}(a) \le x \text{ and } F_{\text{par}}(a) \le F_{\lim}(a)). \tag{47}$$

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 30. The set of TAC policies is defined as

$$Q^*(x) = (\omega F_{\text{par}}(n^*(x)) + (1-\omega) F^*_{\text{pa}}(x))x, \tag{48}$$

where upper viable or precautionary TAC associated with $F^*_{\text{pa}}(x)$ correspond to

$$F^*_{\text{pa}}(x) = \min\left(\alpha(n^*(x))px - \beta(n^*(x)), 1 - \frac{f^{-1}(x_{\lim}(n^*(x)))}{x}\right). \tag{49}$$

4. Numerical example

To illustrate these analytical results, we use a simplified model of the nephrops fishery in the Bay of Biscay, based on which previous research showed that the fishery had gone through a period of excess capacity in the early 1990s. The fishery is subject to a Total Allowable Catch set at the European level, as well as limited entry and a number of technical measures relating to the selectivity of trawling [42]. The use of this example should be considered as illustrative, as to best of our knowledge, ITQs have not been proposed as a management tool in this particular fishery. However, the European Union consultation on ‘rights-based’ fisheries management in the new common fisheries policy [1] suggests that the implementation of an ITQ system could possibly occur in the following years. The question of the acceptability in such a context is thus becoming crucial.

We use the model parameter values estimated by Martinet et al. [45], with some specific adaptations. 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. The population dynamics is specified as a Beverton–Holt relation for the biomass:

$$f(x) = \frac{Rx}{1+Sx}, \tag{50}$$

where we set $R = 1.78$ and $S = 253 \times 10^{-7}$ leading to a positive equilibrium carrying capacity $K = 30\,800$ tons defined as $K = (R-1)/S$. The equilibrium function σ is

$$H = \sigma(x) = x\left(1 + \frac{1}{Sx - R}\right). \tag{51}$$

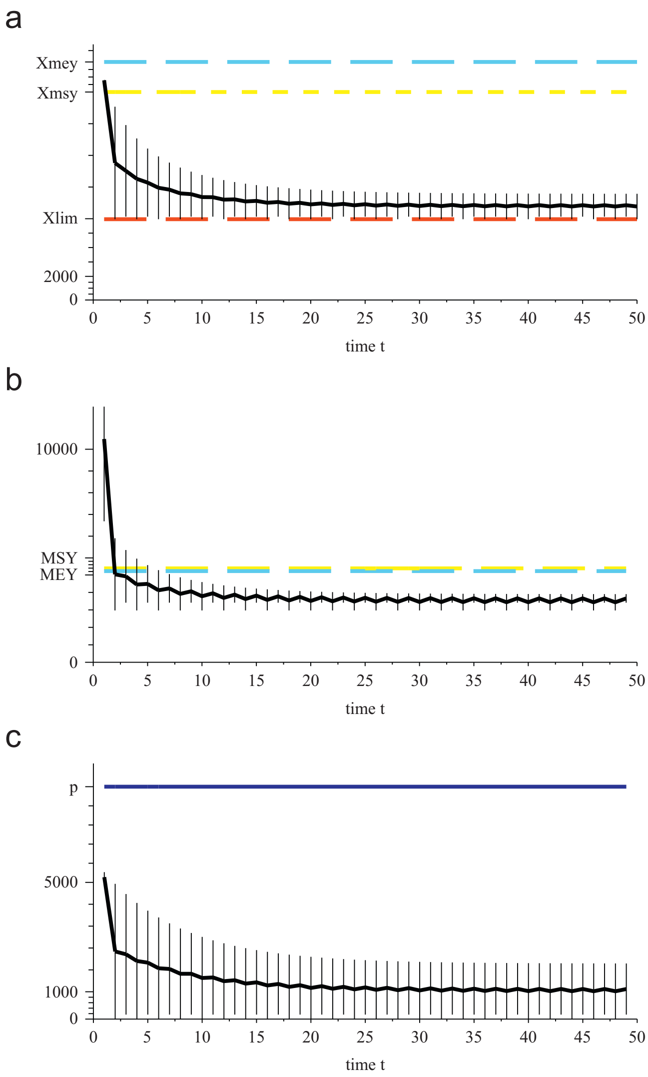

Fig. 4. Viable trajectories (mean and dispersion) in black for $n=235$ agents with initial stock $x_0=18\,600$ tons and *maximin* threshold effort $E_{\lim}=E^*(x_0)=117$ (days at sea). After a declining transition, the stock remains close to the viable threshold $x_{\lim}(n)\approx 6850$ in red. MSY and MEY reference points are in yellow and blue: (a) stock $x(t)$ (tons); (b) quotas $Q(t)$ (tons); and (c) rental price $m(t)$ (euros/tons). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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

$$x_{\text{MSY}}=\frac{R+\sqrt{R}}{S},\quad H_{\text{MSY}}=\frac{(R+\sqrt{R})^2}{S}. \tag{52}$$

We obtain $x_{\text{MSY}}\approx 17\,604$ tons and $H_{\text{MSY}}\approx 4409$ tons. The price of the resource is set at $p=8500$ euros per ton.[10]

The initial stock of the resource estimated at year $t_0=2003$ is set at $x_0=18\,600$ 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:

$$C_i(E)=70\,000+c_{1,i}E+0.1E^2, \tag{53}$$

[10] Based on Le Floc'h et al. [40], the assumption of a fixed landing price could be justified by the observation that landings by the French trawler fleet which targets nephrops in the Bay of Biscay contribute a relatively small share of the total supply to the French market on which the production is sold (between 18% and 35% over the 1990–2005 period). Moreover, as stressed by Le Floc'h et al. [40], while French fleets land mainly live product, other sources of supply concern mainly frozen product, such that there may be a degree of segmentation and a possibility for landing prices in the fishery to respond to fluctuations in landings. Moreover, our model does not account for size-dependent pricing in this fishery [43]. Considering the implications of selectivity and size-dependent pricing is beyond the scope of this paper, but offers interesting perspectives for further research.

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where effort stands for days at sea per year. We introduce heterogeneity between 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 $q_i = 72 \times 10^{-7}$ 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 Fig. 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 $x_{\lim}(n) \approx 6936 < x_0$. 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 $x_{\lim}(a) \approx 6936$ compared to MSY or MEY reference points. Similarly the rental 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 $t_0 = 2003$. If the regulating agency aims at ensuring such an (status quo) effort $E_{\lim} = 163$, Proposition 5 suggests that the maximal number of viable vessels which is strictly lower than n=235 is $n^*(x_0) \approx 214$. To illustrate our results, we reduce the system to $a = 150 < n^*(x_0)$ viable licensed users. The TAC policy is only implemented for these viable users. Under this new scenario, the viability stock threshold $x_{\lim}(a) = 6755 < x_0$ is reduced. This generates the viable trajectories depicted in Fig. 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 the MSY (red) or MEY (blue) reference points.

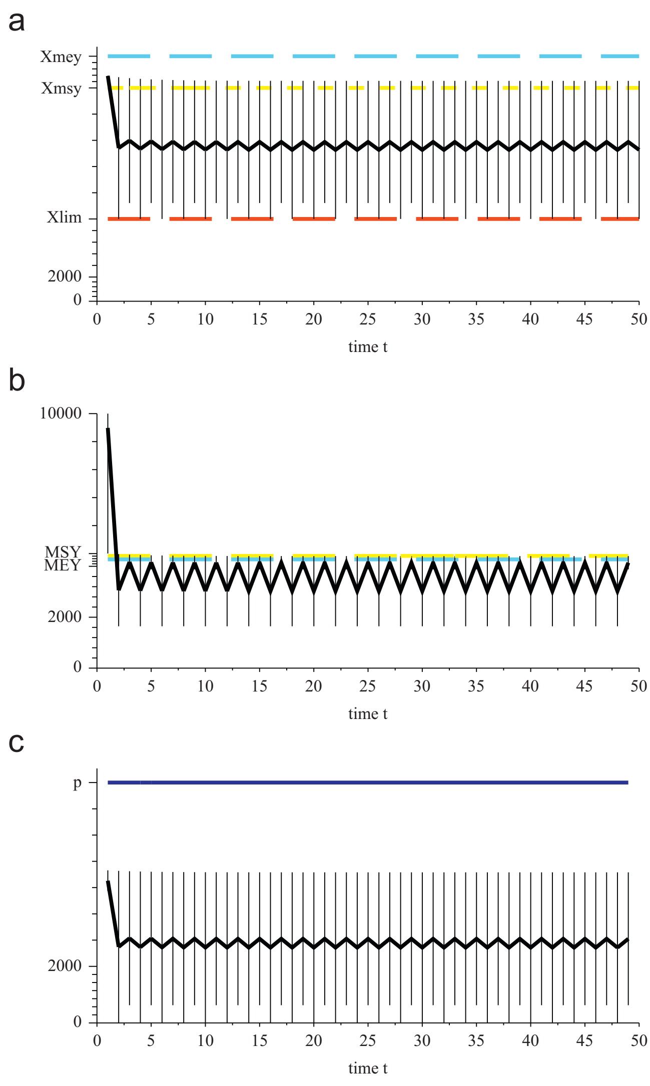

Fig. 5. Viable trajectories (mean and dispersion) in black for $n = 150 < n^*(x_0) = 214$ agents with initial stock $x_0 = 18\,600$ tons and *maximin* threshold effort $E_{\lim} = 163$ (days at sea). Note that, in this case, the mean stock and the total catches increase compared to the n=235 scenario. In particular the mean stock and total catches reach values closer to MSY (yellow) or MEY (blue) reference points: (a) stock $x(t)$ (tons); (b) quotas $Q(t)$ (tons); and (c) rental price $m(t)$ (euros/tons). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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5. Conclusion

This paper addresses the sustainable management of a fishery 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 the net profits associated with fishing. Assuming that regulation of the fishery is achieved through the selection of a TAC schedule, 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 [5,35,6]. 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 [51,48,14], our model also suggests that social goals may potentially be achieved under these management regimes.

However, results show that the ITQ management system is viable in a triple bottom line sense only under very specific conditions. This emphasizes the fact that ITQs are not a panacea and should be designed carefully as suggested by Sumaila [52].

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. This guaranteed level of effort may differ from a status quo regime.

Secondly, our analysis also emphasizes the fact that the social constraint entails a stock conservation 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 goals. This is because if the resource decreases below a critical level, it will not be possible to ensure that all agents remain active. Hence the requests for increased catching possibilities often observed in fisheries with excess capacity may in fact be in contradiction with the social objective of maintaining as many fishers as possible active, including the least efficient—low income fishers. The more participants there are in a fishery, the more sustaining this social objective would in principle require strict conservation and stock rebuilding strategies.

Thirdly, different TAC levels can be selected, among a specific set of viable regulations. This flexibility underlying the set of viable TACs allows for varying balances between the different dimensions of the triple bottom line in an adaptive fisheries management context. By contrast, analysis of IQ systems (without a quota market) leads to identify a unique viable TAC level, implying a more rigid management system.

Lastly, 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 shows the reduction in fleet size which should occur under ITQs, as mentioned in Kompas and Che [38] and in Pinkerton and Edwards [49]. More generally, in a context of excess capacity, the decision maker faces the trade-off of reducing either the current effort and/or the number of active agents. *Maximin* effort and maximal number of viable agents provide the upper and lower bounds of this trade-off.

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 desirability and practical feasibility of the approach itself.

6. Proofs

We basically refer to methods and results detailed in Saint-Pierre [50], De Lara and Doyen [16], Doyen and De Lara [18] 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

$$\mathrm{Viab}(T,T) = \{x \mid x \geq x_{\lim}\}. \quad (54)$$

For any time $t = 0, 1, \ldots, T-1$, 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:

$$\mathrm{Viab}(t-1,T) = \{x \geq x_{\lim}, \exists Q \mid f(x-Q) \in \mathrm{Viab}(t,T)\}. \quad (55)$$

To compute the viability kernel Viab for an infinite horizon $T = +\infty$ as in the definition (26), we write

$$\mathrm{Viab} = \bigcap_T \mathrm{Viab}(0,T). \quad (56)$$

We first claim that:

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Lemma 1.

$$\mathrm{Viab}(t,T)=\begin{cases}[x_{\lim},+\infty[& \text{if } F_{\mathrm{par}}\le F_{\lim},\\ [x_{\lim}(T-t),+\infty[& \text{if } F_{\mathrm{par}}>F_{\lim},\end{cases} \tag{57}$$

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

$$x_{\lim}(t+1)=\frac{f^{-1}(x_{\lim}(t))}{1-F_{\mathrm{par}}},\quad x_{\lim}(0)=x_{\lim}. \tag{58}$$

The proof of Lemma 1 is provided later on in Section 6.2. Assuming for a while that it holds true, we deduce the shape of the viability kernel Viab defined in (56) for an infinite horizon $T=+\infty$.

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

$$\mathrm{Viab}=\bigcap_T \mathrm{Viab}(0,T)=\bigcap_T [x_{\lim},+\infty[=[x_{\lim},+\infty[. \tag{59}$$

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

$$\mathrm{Viab}=\bigcap_T \mathrm{Viab}(0,T)=\bigcap_T [x_{\lim}(T),+\infty[=[\sup_T x_{\lim}(T),+\infty[=\emptyset, \tag{60}$$

since

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

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

$$\frac{x_{\lim}(t+1)}{x_{\lim}(t)}\ge 1+\varepsilon,$$

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

$$\frac{x_{\lim}(t+1)}{x_{\lim}(t)}=\frac{f^{-1}(x_{\lim}(t))}{x_{\lim}(t)(1-F_{\mathrm{par}})}\ge\frac{1}{1-F_{\mathrm{par}}}\frac{f^{-1}(x_{\lim})}{x_{\lim}}=\frac{1-F_{\lim}}{1-F_{\mathrm{par}}}=1+\varepsilon.$$

Finally we induce that

$$x_{\lim}(t)=x_{\lim}(1+\varepsilon)^t, \tag{61}$$

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 (54) and the fact that

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

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 (55), we deduce that $x\ge x_{\lim}$ 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

$$\alpha px-\beta\ge\frac{Q}{x}\ge F_{\mathrm{par}}\quad\text{and}\quad f(x-Q)\ge x_{\lim}(T-(t+1)), \tag{62}$$

which yields

$$x-f^{-1}(x_{\lim}(T-t-1))\ge Q\ge F_{par}x. \tag{63}$$

This implies

$$x\ge\frac{f^{-1}(x_{\lim}(T-t-1))}{1-F_{\mathrm{par}}}. \tag{64}$$

By virtue of the sequence (58), this is equivalent to

$$x\ge x_{\lim}(T-t). \tag{65}$$

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

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

We now distinguish the two cases.

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

$$F_{par} \leq F_{\lim} \Longrightarrow F_{par} \leq 1 - \frac{f^{-1}(x_{\lim})}{x_{\lim}} \Longrightarrow F_{par} \leq 1 - \frac{f^{-1}(x_{\lim}(t))}{x_{\lim}}. \tag{66}$$

In other words, we have

$$x_{\lim} \geq \frac{f^{-1}(x_{\lim}(t))}{1-F_{par}} = x_{\lim}(t+1), \tag{67}$$

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

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

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

$$E^*(x) = \max(E_{\lim} | x \geq x_{\lim},\ F_{\lim} \geq F_{par}) = \max(E_{\lim} | x \geq x_{\lim},\ V^{-1}(0) \geq x_{\lim}). \tag{68}$$

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

$$E^*(x) = \max(E_{\lim} | x \geq x_{\lim}). \tag{69}$$

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

$$E_{\lim} \leq \min_i \frac{pq_i x - c_{1,i}}{c_{2,i}}. \tag{70}$$

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

Acknowledgments

This work was supported by the ANR (French National Agency for Research) through the project entitled ADHOC. We wish to thank the editor and two anonymous referees for their comments and suggestions.

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