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# Voluntary Management of Fisheries under an Uncertain Background Legislative Threat

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**Abstract**

We investigate the possibility for governance authorities to avoid a large part of regulatory costs, by simply backing up social norms with a threat of collective punishment. Specifically, we consider the case of fisheries in which the regulatory cap is to sustain an optimal conservation level. We identify a mandatory regulation such that, when it is used as a threat, it ensures that the cap is voluntarily implemented. The mandatory scheme is based on a incentive mechanism which secures the returns of the harvester, and a tax on potential capacity. From the status of mere threat, this mandatory regulation takes time to be enforced though. We show that such a tax scheme, even if it is applied randomly after the first occurrence of a deviation from the optimal conservation level, ensures voluntary compliance, provided a suitable choice of the capacity tax. We study the properties of this tax scheme and build an example using data on the scallop fishery in the Saint-Brieuc Bay (France) to illustrate our point.

*Key words:* Voluntary agreements, Fisheries, Conservation Policies
*JEL classification*: Q22, Q28

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## 1. Introduction

Collective voluntary approaches commonly refer to commitments of groups of firms, possibly an entire industry, to cutting voluntarily their polluting emissions[1]. These proactive behavior may be motivated by a background regulatory threat, whether enacted[2] or merely potential (Glachant [21]). While both cases fall under the particular denomination of voluntary-threat (V-T) approaches (Segerson and Miceli [47],[48]), the present work strictly focuses on the latter.

Regulatory threats are, in the prolific theoretical literature on voluntary approaches to environmental protection, only one reason among many why firms behave proactively. For instance, a second explanation suggests[3] it allows them to build a green reputation and reach the new markets for eco-friendly goods and services. Another points out[4] strategical signaling (in order to trigger tougher regulation) as a motive for overcompliance to environmental standard.

But voluntary approaches do not solely differ in terms of driving forces : most importantly, strongly depending on preexisting regulatory structures, they come in as many forms as institutional and legal backgrounds. A widely adopted classification distinguishes between three main categories[5], set on the basis of the regulatory agency involvement level (OECD Report [37]) : (i) *public voluntary programs* (the agency elaborates engagements, to which the firms may voluntarily subscript) ; (ii) *negotiated agreements* (the engagements are collaboratively elaborated by the voluntary firms and the agency) ; and (iii) *unilateral commitments* (the engagements are elaborated by the voluntary firms).

While, in theory, V-T policies may possibly assume each of the three institutional forms aforementioned, in the field, they turn out to be most often related to policies scenarios of type (i) and (ii), with collective liability rules. Indeed, when potential enactments are sectoral, responsibility naturally emerges as collective (as well as the free-riding incentives that come along, see for instance Brau and Carraro [9]).

In this study, we choose to present a V-T policy with an environmental standard set by the regulator alone, as in type (i), and a punishment which applies to the group regardless of individual voluntary efforts. So far, such collective V-T approaches have been mainly studied as *de facto* arrangements in standard contexts of pollution regulation (e.g. see Segerson and Wu [49], Dawson and Segerson [17], or Brau and Carraro [9]). The aim of the present work is therefore twofold. First, it shifts toward a normative perspective (as in the recent Suter et al. [51], Chiambretto and Stahn [14]), by parametrizing the threat

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[1] Two examples are the EPA 33/50 Program (evaluated by Arora-Cason [2]), and the ACEA agreement, pursued in the US and EU respectively.

[2] E.g. when used in a policy mix coupled with command and control, see Borkey et al. [8])

[3] E.g. Arora and Gangopadhyay [3]; Cavaliere [12]; Bagnoli and Watts [5]; Ahmed and Segerson [1]. See Lyon and Maxwell [35] for a comprehensive review of articles based on this explanatory hypothesis.

[4] E.g. Denicolo [18]; Fleckinger and Glachant [19].

[5] Some classifications may also include direct negotiations or Cosean bargaining (e.g. Rhoads and Shogren [41]) as a fourth category, and consider information disclosure along with eco-certification schemes (for fisheries see Brécard et al. [10]) as a distinct kind of voluntary approaches.

so as to ensure it becomes an efficient *mechanism.* Second, it suggests extending the analysis to the regulation of dynamic externalities that are peculiar to common property resources (CPRs) management issues. Specifically, we consider the case of renewable fish stocks and the regulation of its persistent overexploitation.

The tragedy of the commons (Hardin [27]) with respect to fisheries has been investigated in an extensive theoretical literature, subsequent to the seminal works of Gordon [22] and Clark and Gordon [15]. Combining dynamic and game-theoretic approaches with the biological specificities of fish stocks, it provides us with a wide range of open access resource games and describes the underlying incentive structure as follows. When several agents exploit a same resource, the quantity they decide to harvest affects other agents' payoffs in two ways : (i) it affects the unit return of harvesting for all harvesters at the current period and (ii) it impacts the size of the fringe to harvest for the future periods resulting in a variation in harvest unit cost. Via harvesters' incentive to free-ride on responsible behaviors of others, these two externalities may lead to the underprovision of what can be considered as a public good: stock conservation.

Supported by case studies[6], a growing strand of theoretical literature exhibits cooperative equilibria for CPRs (see Ostrom [38] for a review) that implement socially desirable outcomes, which amounts someway (refering to our previous terminology) to study voluntary agreements of types (iii). This problem has already been explored in several directions. Indeed, game theory (see Bailey et al. [6] for a review) helps to delineate situations in which the cooperative outcome can be obtained as a competitive subgame perfect equilibrium (Polasky et al. [39], Tarui et al. [53]) or, taking more a cooperative view (see Pintassilgo et al [40] for a review), studies bargaining solutions, standard coalitional games (see Lindroos et al. [33] for a review), and even coalition formation (especially the case of international agreements). Other works investigate the consequences of the introduction of context dependant behaviors, like conditional cooperation motivations (Richter and Grasman [42]) or status seeking behaviors (Long and McWhinnie [34]). Finally another branch of contributions points out the specific social norms and/or institutional background necessary for these equilibria to emerge (Vincent [54], Gutiérrez et al. [26], Basurto and Coleman [7]).

However, despite initiatives for governance, the depletion of marine resources remains a pervasive phenomenon, as shown by several empirical studies (e.g. McWhinnie [36]), and witnessed by actual efforts of international organizations like The United Nation (UN) for relevant global agreements to be reached. In particular, the Doha Round's negotiation for an improved discipline on fisheries subsidies (Swartz and Sumaila [52]), or the Immediate Plan of Action agenda of the Food and Agriculture Organization (FAO)'s Fisheries and Aquaculture Department (2009-2011), are recent international acknowledgement of the need for aligned regulations by external authorities.

The UN Fish Stocks Agreement of 1995 and the apparatus of command and control tools available to Regional Fisheries Organizations (RFOs), do make sustainability of

[6] For recent case studies see for instance Haynie et al [29], Cavalcanti et al. [11] or Sarker et al.[43].

marine resources attainable. Several types of regulation mechanism were implemented in the last twenty years. They ranged from standard command and control measures (restrictions on targeted species or fish size, gears, areas or seasons of extraction etc.) to concessions-managed fisheries with or without limited tenure (Costello and Kaffine [24], Costello, Querou and Tomini [25]). We may as well cite market-based instruments like Individual Transferable Quotas (Costello et al [23]), or the developement of marine protected areas (Smith and Willem [50]). All these various regulation mechanisms clearly prevent the fishery collapse mentioned above and, in some cases, even contribute to the development of conscious practices. But are such policies sustainable in themselves ? This undoubtedly raises the old question of "the cost of fishery management" (Schrank et al.[45]). Even if the risk of fishery collapse or the argument of population restoration can be advocated in the short term to validate the social cost, a long term conservation policy should also try to minimize this burden. This is exactly one of the ambitions of voluntary regulation schemes.

In this paper we thus investigate the possibility for regulatory authorities to avoid a large part of regulatory costs, by simply backing up social norms with a threat of collective punishment, when a mandatory regulation is expected to be difficult to enforce. Specifically, we consider, in a conservation rational, the case in which the regulatory cap is to sustain a stationary extraction level, after it was first reached by a mandatory regulation policy. Moreover, focusing on voluntary approaches of type (i), we identify a mandatory regulation such that when it is used as a threat, the cap is ensured to be voluntarily implemented, while limiting the administrative requirements to the monitoring process of the total stock level. This perspective differs from the discussion on fishing regulation and imperfect monitoring since we feature a device involving no legislative or administrative implementation step of any sort. In particular, it is structurally dissimilar to mandatory regulations with 0-monitoring, sometimes mentioned as benchmark case in this literature. Our contribution also substantially differs from the prolific literature about cooperative equilibria previously mentioned, in which self-regulation relies on harvesters' threats to punish each other and not on the intervention of an external regulating body.

To our knowledge, very few papers explicitly mention voluntary conservation agreements in a fishery context. Langpap-Wu [31] and Langpap [30] address the question of the conservation of endangered species but their approach mainly covers terrestrial species living on private lands. Specifically, they consider the likelihood of a negotiated V-T policy (i.e. of type (ii) in our previous terminology) in a two period model with uncertainty on the survival of the species, irreversible investment in conservation, and in which, when negotiations fail, there is some probability that a mandatory policy is implemented. In contrast, our analysis considers a continuous time setting without uncertainty and consider V-T approaches of type (i). In addition, we explicitly assume that the mandatory policy takes some random time to activate after a deviation from the optimal conservation level was observed. The complex political processes (due to lobbying, legislature, etc.[7])

[7] See Lyon and Maxwell [19] or again Glachant [21] for examples of the modeling of such processes.

and the practical enforcement itself, mainly explain this delay and its randomness[8] in our model.

Finally, Cave [13] proposes an hybrid approach mixing history-dependent strategies and bargaining theory, in the standard discrete harvesting model of Levhari and Mirman [32]. It exhibits the emerging cooperative equilibria under a threat to reverse to the competitive outcome if one harvester defects from cooperation, knowing there will be room for renegociation in a further step. Again, Cave's work refers to agreements that are not preemptive in nature, but purely voluntary. Such agreements emerge from harvesters' incentive to overcome the tragedy of the commons, and they do not primarily aim at avoiding a potential enactment. Conversely, our setting relies on a collective tax-threat which, at most, could also be interpreted as a substitute for the lacking social norms and/or institutional background necessary for cooperation to take shape within harvesters.

To be more specific, as will be detailed in the main text, the threatened sanction is a two-part scheme : first, an insurance mechanism, indexed on stock level, guarantees that the cap is implemented when it is enforced, while ensuring a stationary profit level to harvesters whatever the actual level of fish stock at the starting time of implementation may be ; second, a tax on excess capacity discourages unilateral deviations from the stationary standard. We then show how such a tax threat should be optimally design for the standard to be voluntarily met by harvesters (normative approach), and specifically that it must depend on the enforcement delay of the mandatory scheme.

The rest of the article is organized as follows. The basic framework is described in the next section. Section 3 sets the regulator's environmental target. In section 4, we present the collective V-T policy, and derive some useful properties in section 5. Section 6 studies the problem of a candidate to deviation under the collective V-T policy. In section 7, a sufficient condition on the tax threat for the standard to be voluntary met is stated along with a budget balance condition. Both conditions are illustrated in the numerical example from section 8, before section 9 concludes. Technical proves are relegated to the appendix.

## 2. A simple bio-economic model

Consider $N > 1$ symmetrical agents, indexed by $i$, who jointly harvest a common property renewable resource over an infinite horizon, $[0, +\infty[$. The resource stock at time $t$, measured in units of biomass, is denoted by $S(t)$. Our analysis builds upon the widely used Gordon-Schaefer model of fisheries (see among others Clark [16]). Accordingly, $S(t)$ is assumed to evolve over time due to natural growth and harvest. Stock growth is constrained by $K$, the carrying capacity of the resource, so that $S(t) \in [0, K]$. The maximal harvest per capita at time $t$ is given by $qS(t)$, where $q$ is a coefficient of catchability which

[8] Here, it is the duration of the delay, as opposed to whether the mandatory regulation is eventually implemented or not, that is random.

reflects both the size and the maximal extraction capacity of one player's fleet. A measure of excess capacity is provided by comparison with the individual effective harvesting, $qS(t)e_i(t)$. The effort variable, $e_i(t) \in [0,1]$, captures the combined flow of labour and capital services raised by $i$ for purpose of extraction. It is therefore assumed that the actual yield is linear in effort. The resource grows at a natural rate $r(S)$ which decreases with the size of the biomass, $r'(S) < 0$, and stops growing when $K$ is reached, $r(K) = 0$. We furthermore assume that the maximal growth rate $r(0)$ is bounded and that $r"(S) \leq 0$, meaning that the rate of growth decreases over $[0, K]$ at an increasing rate. From these observations, we can define the dynamics of the biomass as follows:

$$\frac{\dot{S}(t)}{S(t)} = r(S(t)) - q\left(\sum\nolimits_{i=1}^{N} e_i(t)\right), \text{ with } S(0) = \bar{S} \text{ the initial state.} \tag{1}$$

Still in the Gordon-Schaefer ([22], [44]) tradition, we assume that the yields are sold on a competitive market and that the instantaneous profit of each harvester is proportional to his effort. We denote by $\pi(S)$ the profit per unit of effort, and assume that there exists a minimal biomass stock, $S_{\min}$, for which this profit becomes positive[9]. It must also be noticed that a same extraction rate $qe_i(t)$, leads to higher captures if applied to a larger biomass. This implies, at least under a pure competition, that the profit per unit of effort increases with the biomass, $\pi'(S) > 0$. We nevertheless assume that the elasticity, $\varepsilon_\pi(S) = \left(\frac{\pi'(S)S}{\pi(S)}\right)$, of this function decreases for all $S > S_{\min}$. In particular, a same proportional increase of the biomass has less than a proportional impact on the profit for a larger biomass[10]. Each agent, then, seeks to maximize the present value of its instantaneous profit derived from harvesting the resource. With $\rho > 0$ denoting the discount rate, harvester $i$'s present return is given by:

$$R_i(S(t), e_i(t)) = \int_0^{+\infty} \exp(-\rho t)\pi\left(S(t)\right)e_i(t)dt. \tag{2}$$

Finally, let us notice that the catchability coefficient $q$ can also be viewed as the individual maximal rate of depletion of the resource. Since the present paper aims at considering endangered resources, we assume that the total rate of depletion is larger than the growth rate of the biomass for which it becomes profitable to harvest, $nq > r(S_{\min})$. Such an hypothesis clearly brings the question of the relationship between the maximal harvesting effort and the optimal conservation target, which will be studied in the next section.

[9] This is, for instance, the case, if the fish stock is sold at a competitive price $p$ and the marginal cost $c$ per unit of effort is constant since $\pi(S) = (pqS - c)$.

[10] This property is, for instance, satisfied if $\pi(S)$ is concave and if the average profit rate is, on $[S_{\min}, K]$, lower than the marginal profit rate. But in its present form, this assumption does not imply these two restrictions.

## 3. The optimal conservation target

Before we start presenting the mechanism of voluntary biomass regulation, let us define the endogenous optimal conservation level to be targeted by the policy. In our framework, we implicitly assume that the fish market is competitive, which involves, in particular, that over-exploitation is a consequence of common property solely. The optimal conservation level can therefore be viewed as the steady state that solves the joint-rent maximization problem. Let us denote by $S^*$ this steady state, and write the optimization program as follows:

$$\max_{(e_i(t))_{i=1}^N \in [0,1]^N} \int_0^{+\infty} \exp(-\rho t) \left( \pi(S(t)) \left( \sum\nolimits_{i=1}^n e_i(t) \right) \right) dt \tag{3a}$$

$$st. \quad \dot{S}(t) = S(t) \left( r(S(t)) - q \left( \sum\nolimits_{i=1}^n e_i(t) \right) \right) \ , \ S(0) = \bar{S} > 0. \tag{3b}$$

Since the instantaneous return as well as the dynamics are linear in the total harvesting effort, it can even be expressed as the following variational problem:

$$\max_{\dot{S}(t)} \int_0^{+\infty} \underbrace{\tfrac{\exp(-\rho t)}{q} \left( \pi(S(t)) \left( r(S(t)) - \tfrac{\dot{S}(t)}{S(t)} \right) \right)}_{f\left(S(t),\dot{S}(t),t\right)} dt \tag{4}$$

$$\text{with} \quad \tfrac{\dot{S}(t)}{S(t)} \in \left[ r(S(t)) - nqS(t), r(S(t)) \right]. \tag{5}$$

From the Euler-Lagrange condition, we know that:

$$\frac{\partial f}{\partial S} = \frac{d}{dt} \frac{\partial f}{\partial \dot{S}} \Leftrightarrow \underbrace{\left( \tfrac{\rho}{S} - r'(S) \right) \pi(S) - \pi'(S) r(S)}_{:=\phi_{FB}(S)} = 0 \tag{6}$$

and it can be shown that:

**Lemma 1.** *There exists a unique solution $S^* \in (S_{\min}, K)$ to Eq.(6) and $\forall S \in [S_{\min}, K]$ if $S < S^*$ (resp. $>$) then $\phi_{FB}(S) < 0$ (resp. $>$).*

This (singular) solution $S^*$ will be identified to the long term sustainable biomass. Moreover, from the dynamics (see Eq.(3b)), we deduce the symmetric individual effort level which maintains the resource at $S^*$. This sustainable effort $e^*$ is:

$$\forall i, \quad e_i^* = e^* = \frac{r(S^*)}{nq} \in (0, 1) \tag{7}$$

It is no surprise $e^*$ must be strictly lower than one since we consider the case of endangered species, i.e. $r(S^*) > r(S_{\min}) > nq$. Finally, if this optimal conservation target is met, the current long term profit of a harvester will be:

$$v_{FB} = \tfrac{\pi(S^*) r(S^*)}{nq} = \pi\left(S^*\right) e^* \tag{8}$$

We can even go one step further. Following Hartl and Feichtinger [28] or Sethi [46], we know that the optimal solution of this program is given by the most rapid approach path (hereafter referred to as the MRAP) to $S^*$. As a result, if the initial stock $S_0$ falls below $S^*$, the optimal approach to the stationary state involves no extraction during a recovery period, until $S^*$ is reached at some switching-time. Then, the steady state is sustained by the regular effort levels, $e^*$. Conversely, if the trajectory is initiated in $S_0 \geq S^*$, the maximal harvesting effort is required from each harvester until $S^*$ is reached, and from which they must collectively reverse to $e^*$. More precisely, it can be stated that:

**Proposition 1.** *Under our assumptions, the path of the biomass that is solution to problem (3a), is given by $S^{FB}(t, \bar{S})$, the MRAP to the optimal conservation level, $S^*$. The latter is reached in finite time $T(\bar{S})$ and is supported by an individual optimal Markovian effort $e^{FB}(S(t))$, which is either 0 or 1 depending whether $S(t) \lesseqgtr S^*$, and switches to $e_i^*$, the sustainable effort, when $S(t) = S^c$.*

**Remark 1.** *We observe for later use that the previous optimization problem can be considered as starting at time $T$ and state $S$. In this case, the optimal stationary levels of resource and effort remain identical to $S^*$ and $e^*$ respectively, while the optimal state trajectory becomes $S_T^{FB}(t, S) := S^{FB}(t - T, S)$. The same Markovian rule, $e^{FB}(S(t))$, generates the optimal state trajectory. Finally, the switching time is given by $T'(S) := T + T(S)$.*

It is a well known result of fisheries bioeconomics that the path described in proposition 1 cannot be reached competitively[11] without the implementation of some suited regulation. Indeed, whatever the initial state of the biomass, each harvester may, at some point, benefit from a unilateral deviation by choosing a harvesting effort higher than $e^{FB}(S(t)) < 1$. In particular, let us assume that the optimal conservation level $S^*$ has been reached through the implementation of a short-term drastic policy as, for instance, open access or moratorium, depending whether $S(t) \lesseqgtr S^*$. Then, some long-term regulation policy is still needed to sustain $S^*$. The main question therefore becomes : how can we design a long term voluntary conservation policy based on a potential legislative threat ?

## 4. The V-T conservation mechanism

Let us assume, from now on, that the optimal conservation level is reached, i.e. formally $S_0 := S^*$. The conservation mechanism works as follows: a regulator, who monitors the biomass $S(t)$, makes an ex-ante announcement that a mandatory policy will be implemented if harvesters fail in voluntarily sustaining $S^*$. The mandatory policy relies on a threefold scheme : once it becomes effective, it (i) provides incentives to restore and to maintain the biomass at the optimal conservation level, but it also introduces (ii) a

[11] It is not a purpose of the present paper to re-state this result of the tragedy of the commons in the canonical fishery setting used here. See Clark [16] for a detailed computation of the competitive equilibrium, as well as a proof it leads to a smaller stationary state and a higher symmetrical individual effort than the sole owner solution.

threat, specifically a long lasting taxation on the exceeding harvesting capacities, and (iii) a provision for fisheries return to ensure political acceptability. The purpose behind such an announcement is obviously to enhance ex ante voluntary compliance without having to actually carry out the threat, but, to some extent, it can be viewed as initiating a coordination device. Finally, as an announcement, it must be credible to the harvesters, as well as ratifiable by a legislative body, if necessary, through some political process. In this paper, we do not explicitly model such a process or credibility issues, since the regulator is not exactly a player (conversely to Glachant ([**21**]), for instance), and endogeneity is confined to our true focus, which is how harvesters collectively face the threat. Instead, we directly include some specific constraints into the design of the mandatory regulation, so that the main aspects related to implementability are dealt with.

We first assume that the mandatory regulation scheme takes some time to be active after the deviation occurrence at date $t_{dev}$. The length of this delay is uncertain, since it depends on complex and interdependent political processes such as lobbying and legislature, besides the practical enforcement process itself. From the point of view of the deviator, there is therefore some random delay $\tilde{\Delta}$ during which he can benefit the deviation from the optimal conservation effort. We denote by $F(t) = P\left[\tilde{\Delta} \leq t - t_{dev}\right]$ the cumulative distribution of this delay, where $t > t_{dev}$. For the sake of simplicity, we say that the probability the mandatory regulation becomes active between $t$ and $t + dt$, given that it was not implemented before $t$, is constant. This means, for $dt$ small, that the instantaneous rate of occurrence of the policy is given by:

$$\delta(t) = \lim_{dt \to 0} \frac{P\left[t \leq t_{dev} + \tilde{\Delta} \leq t + dt \;\middle|\; \tilde{\Delta} \geq t_{dev} + t\right]}{dt} = \frac{\dot{F}(t)}{1 - F(t)} = \delta \tag{9}$$

and implies that this random delay variable $\tilde{\Delta}$ is exponentially distributed, with cumulative distribution:

$$\forall t \geq t_{dev}, \quad F(t) = P\left[\tilde{\Delta} \leq t - t_{dev}\right] = 1 - e^{-\delta(t - t_{dev})}, \tag{10}$$

As a consequence, $(1 - F(t)) = e^{-\delta(t - t_{dev})}$ is the probability that the mandatory regulation is not implemented after a delay of $(t - t_{dev})$.

Now, let us call $t_m$ some realization of the starting date of the mandatory regulation. As $t_m > t_{dev}$, the tax scheme must contain an incentive part which restores the optimal conservation level of the biomass. It corresponds to the sum of the profits that the $(n-1)$ other harvesters would obtain by harvesting the current biomass stock $S(t)$ if they all followed the recommendation of the regulator to provide the first best Markovian harvesting effort, $e^{FB}(S)$:

$$\mathcal{I}(S) = (n-1)\pi(S)\, e^{FB}(S) \tag{11}$$

It seems relevant to also introduce a lump-sum tax which neutralizes $\mathcal{I}(S)$'s wealth effects. This may however create a problem of political acceptability. Remember that the tax scheme is simply announced by the regulator and becomes effective only if needed, after some political bargaining process that we do not model implicitly. In order to ensure the credibility of the announcement, we assume that this lump-sum transfer does more than just balancing the incentive subsidy. Specifically, it is design so as to guarantee each harvester a remuneration corresponding to the individual profit that he would have made if no deviation had occurred beforehand. In particular, consider any deviation causing the biomass stock to stand below its optimal conservation level in $t_m$. In this case, the optimal management strategy (see proposition 1) would require, at least in the short term, a moratorium. Then, during this period, our incentive scheme secures the current harvester returns to $\pi(S^*)e^*$, which are the long run instantaneous returns under compliance. So, denoting by $S_{t_m}^{FB}(t, S_{t_m})$ the first best biomass path starting a date $t_m$ with a initial stock of $S_{t_m}$ (see remark 1), this lump-sum tax with secured returns is given by:

$$\mathcal{L}(S^*, t) = n\pi\left(S_{t_m}^{FB}(t, S_{t_m})\right) e^{FB}\left(S_{t_m}^{FB}(t, S_{t_m})\right) - \pi(S^*)e^* \tag{12}$$

Such a transfer policy is obviously insufficient per se to encourage the harvesters to opt for the ex-ante voluntary compliance. The full mandatory regulation scheme must therefore include some mechanism which deterministically deters deviation, even though the implementation starting date is actually random. We suggest adding a taxation on the potential profits that could be derived from the harvesting capacities that exceed the capacity level maintaining the biomass at its optimal conservation level. Specifically, we know the catchability coefficient induces an individual maximal harvest of $qS^*$ at the optimal conservation level, while the fishing capacity that actually sustains this level is given by $qe^*S^* = \frac{r(S^*)S^*}{n}$. Now, remark that the profit function $\pi(S)$ is expressed per unit of effort, hence such an excess capacity taxation rule can be written as:

$$\mathcal{T}(S^*, \tau_x) = \pi(S^*)\left(1 - \frac{r(S^*)}{nq}\right)\tau_x, \tag{13}$$

where $\tau_x$ is endogenously determined so as to guarantee consistency of the voluntary mechanism in two ways. First, it should convince the fisheries to meet the regulation cap voluntarily, i.e. without any need to implement the mandatory regulation scheme. Second, it should also be set at a level such that the mandatory regulation scheme is credible. Indeed, any potential deviator may reasonably expect that this long lasting capacity taxation covers the costs generated by the secured return principle, so that the regulator will not come back on his decision to implement the regulatory scheme. To be more specific, the deviator's expectations on the evolution of the biomass due to his new effort choice must be, at each instant, consistent with a potential activation of the mandatory regulation which should be, at least, budget balancing.

To summarize this discussion, we can say:

**Definition 1.** *The V-T conservation mechanism, $\mathcal{M}(S, S^*, t, \tau_x) = \mathcal{I}(S) - \mathcal{L}(S^*, t) - \mathcal{T}(S^*, \tau_x)$, is announced by the regulator and implemented after a random delay ($t_m - t_{dev}$) that follows the first deviation (Eq.(10)). It relies on an incentive part (Eq.(11)), a lump-sum transfert which secured returns for political acceptability (Eq.(12)) and a deterrent* *part based on an endogenous taxation of the excess harvesting capacity (Eq.(13)). The tax rate, $\tau_x$, is chosen so that the optimal conservation level is met voluntarily and the credibility of the mechanism is ensured.*

## 5. The properties of the background mandatory scheme

Let us assume, in this section, that the regulator has observed a deviation from the optimal conservation level $S^*$ and that we are eventually at $t_m$, i.e. when the mandatory scheme is activated given the current state, $S_{t_m}$, of the biomass. We have now to check whether the mandatory tax scheme does perform as design. At that date, the present value of the profit of each harvester is:

$$\int_{t_m}^{+\infty} e^{-\rho(t-t_m)} \left(\pi(S(t))e_i(t) + \mathcal{M}\left(S(t), S^*, t, \tau_x\right)\right) dt \tag{14}$$

and one should first expect, if the mechanism is efficient, that it restores, in an harvesting game starting at $t_m$, the first best extraction path $S_{t_m}^{FB}(t, S_{t_m})$ starting in state $S_{t_m}$ (see remark 1). As planned, this is exactly what the pure incentive part (see Eq.(11)) of the tax scheme seems doing. Indeed, if each harvester receives a state dependent subsidy of $(n-1)\pi\left(S\right)e^{FB}(S)$, he internalizes the externalities that drive the tragedy of the common. Moreover, since the other parts of $\mathcal{M}\left(S, S^*, t, \tau_x\right)$, namely the lump-sum transfer and the capacity taxation, are independent of the current biomass and the harvesting effort, each harvester chooses his optimal effort by solving:

$$\max_{e_i(t)} \int_{t_m}^{+\infty} e^{-\rho t} \left(\pi(S(t)e_i(t) + (n-1)\, e^{FB}\left(S(t)\right)\right) dt \tag{15}$$

$$\frac{\dot{S}(t)}{S(t)} = r(S(t)) - q\left(e_i(t) + (n-1)\, e^{FB}\left(S(t)\right)\right),\ S(t_m) = S_{t_m}$$

Again, this program can be transformed into the following variational problem:

$$\max_{\dot{S}(t)} \int_{t_m}^{+\infty} \frac{e^{-\delta t}}{q} \left(\pi(S(t)) \left(r(S(t)) - \tfrac{\dot{S}(t)}{S(t)}\right)\right) dt \tag{16}$$

$$\text{with} \quad \tfrac{\dot{S}(t)}{S(t)} \in \left[r(S(t)) - \left(1 + (n-1)\, e^{FB}\left(S(t)\right)\right), r(S(t)) - (n-1)\, e^{FB}\left(S(t)\right)\right].$$

It remains to notice this singular problem leads to the same Euler-Lagrange condition (see Eq.(6)) as the optimal conservation problem (Eq.(4)). As a consequence, the stationary conservation level will be $S^*$ and each player will adopt a MRAP strategy in order to reach this steady state, i.e. choose the first best harvesting effort $e^{FB}\left(S\right)$. We can therefore state:

**Proposition 2.** *The first best harvesting effort, $e^{FB}\left(S\right)$, played by all harvesters, is a Markovian equilibrium of the harvesting game starting at $t_m$, i.e. after the activation of the mandatory policy.*

The mandatory part of the tax scheme, while it is implemented, thus ensures the optimal conservation path is restored. However, the primary function of such a tax-scheme is to work as a background threat, which deters the harvesters to deviate from the optimal conservation level. It is therefore crucial to know what a deviator can expect to gain when the policy is enforced : let us then define his current profit after $t_m$. As it drives him to play the Markovian equilibrium strategy, $e^{FB}(S)$, the incentive part of $\mathcal{M}(S, S^*, t, \tau_x)$ that includes the lump-sum transfer simply guarantees to each harvester an instantaneous return of $\pi(S^*)e^*$, which corresponds to the profit he obtains under compliance. Then, recalling he also bears a tax over exceeding capacity (see Eq.(13)), his instantaneous profit after $t_m$ is given by:

$$\begin{aligned} v_{\mathcal{M}}(\tau_x) &= \pi(S^*)e^* - \pi(S^*)\left(1 - \tfrac{r(S^*)}{nq}\right)\tau_x \\ &= \pi(S^*)\left(\tfrac{r(S^*)}{nq}(1+\tau_x) - \tau_x\right) \end{aligned} \tag{17}$$

which one can immediately notice to be constant across time, and independent of the state of the biomass at which the policy is implemented. Such an observation will be helpful in the next section, in which we study the potential gain of a deviator during $[t_{dev}, t_m]$.

## 6. The potential gain from a deviation

We now consider the decision that some harvester $i$ may make, at date $t_{dev}$, to play $e_i(t_{dev}) \neq e^*$ while the collective V-T policy is enforced. In order to assess the expected gain of this deviation, he has to make some conjectures on the behavior of the $(n-1)$ other harvesters. In the Nash tradition, we assume he conjectures the other players follow the prescription of the policy maker by selecting an harvesting effort of $e^*$. Then, he also knows from the ex-ante announcement, that if he deviates, a legislative process will be triggered, and thereby, the mandatory regulation scheme will become enforceable after some random delay. He therefore expects, from this random date, his opponents to change their behavior and adopt the equilibrium strategy $e^{FB}(S(t))$ induced by the mandatory scheme, as depicted in proposition 2. In this situation, the best response of the deviator is also to be compliant and his current payoff is given by $v_{\mathcal{M}}(\tau_x)$ (see Eq.(17)).

Given these conjectures on the behavior of the other harvesters, the deviator evaluates his payoff as follows : before $t_{dev}$, he obtains the long term current first best return $v_{FB}$ described in Eq.(8), whereas after $t_{dev}$, his return becomes uncertain. He thus either obtains the payoff $v_{\mathcal{M}}(\tau_x)$ induced by his best reply to the mandatory policy, or the profit generated by his optimal effort choice as long as the policy is not implemented. Since he also knows the probability $(1 - F(t))$ that the policy in not implemented before $t > t_{dev}$, his expected payoff will be of:

$$\begin{aligned} &V(e(t)_{t>t_{dev}}, \tau_x, t_{dev}) = \\ &\int_0^{t_{dev}} \exp(-\rho t) v_{FB} dt + \int_{t_{dev}}^{+\infty} \exp(-\rho t)\left[\pi(S(t)e_i(t)\left(1 - F(t)\right) + v_{\mathcal{M}}(\tau_x)F(t)\right] dt \end{aligned} \tag{18}$$

Then, the largest gain $\mathcal{V}^{dev}(\tau_x, t_{dev})$ that he obtains from a deviation $(e_i(t))_{t \geq t_{dev}}$ after date $t_{dev}$, actually maximizes, as long as the mandatory scheme is not implemented, the previous quantity under the following expected change of the biomass:

$$\frac{\dot{S}(t)}{S(t)} = r(S(t)) - q\left(e(t) + (n-1)\, e^*\right) \ , \ S(t_{dev}) = S^* \tag{19}$$

Now, observe that not only the equilibrium payoff $v_{\mathcal{M}}(\tau_x)$ resulting from the application of the mandatory regulation scheme but also the first best current payoff $v_{FB}$ are both independent from the harvesting effort and the biomass stock. So if we want to know his optimal deviation strategy, it simply remains to solve:

$$\mathcal{V}^{dev}(\tau_x, t_{dev}) := \max_{(e(t))_{t \geq t_{dev}}} \int_{t_{dev}}^{+\infty} \exp(-\rho t)\pi(S(t))e(t)\left(1 - F(t)\right) dt \tag{20}$$

$$s.t \quad \frac{\dot{S}(t)}{S(t)} = r(S(t)) - q\left(e(t) + (n-1)\, e^*\right) \ , \ S(t_{dev}) = S^* \tag{21}$$

This problem can again be transformed in a variational problem and from the Euler-Lagrange condition, we know that the singular state now solves:

$$\phi_{dev}(S) = \pi(S)\left(\frac{\rho+\delta}{S} - r'\left(S\right)\right) - \pi'(S)\left(r\left(S\right) - (n-1)\, qe^*\right) = 0 \tag{22}$$

We can even say:

**Lemma 2.** *There exists a unique solution $S^{dev} < S^*$ to $\phi_{dev}(S) = 0$ with the property that $S < S^{dev}$ (resp. $>$) we have $\phi_{dev}(S) < 0$ (resp. $>$).*

However, this does not necessarily mean that the optimal effort induced by the MRAP dynamics is feasible. Such a property requires indeed that the long term effort $e^{dev}$, which sustains the steady state of the biomass, $S^{dev}$, belongs to $[0, 1]$, or, in other word, from Eq.(21), that:

$$e^{dev} = \tfrac{1}{q} r(S^{dev}) - (n-1)\, e^* \in [0, 1] \tag{23}$$

Since the biomass grows faster at $S^{dev} < S^*$ than at the optimal conservation level, and the other harvesters maintain $e^*$, it is straightforward $e^{dev} > e^* > 0$. The deviator should therefore harvest more in order to get the biomass to stationate at $S^{dev}$, but has he a sufficiently large harvesting capacity ? If the answer is yes, he plans, as he deviates, to harvest at full capacity until the state $S^{dev}$ is reached and then to switch to $e^{dev}$. But this requires, from Eq.(23), that:

$$r\left(S^{dev}\right) - \tfrac{(n-1)}{n} r(S^*) \leq q \tag{24}$$

In the opposite case, he plans to maintain his effort at the highest level over the whole horizon starting at $t^{dev}$, and this optimal strategy causes the fish stock to slowly decrease, until the policy is implemented, from $S^*$ to a long term steady state $\bar{S}^{dev}$, given by:

$$r(\bar{S}^{dev}) = q\left(1 + (n-1)\, e^*\right) \tag{25}$$

A biomass stock with belong, if condition (24) is not satisfied, to $\left(S^{dev}, S^*\right)$.

From this discussion, we can even conclude that any deviation should occur immediately, i.e. at $t_{dev} = 0$. Indeed, let us differentiate $\mathcal{V}^{dev}(\tau_x, t_{dev})$ with respect to the deviation date:

$$\frac{\partial \mathcal{V}^{dev}(\tau_x, t_{dev})}{\partial t_{dev}} \exp(\rho t_{dev}) = \\ (v_{FB} - [(\pi(S(t_{dev}))e_i(t_{dev}))\,(1 - F(t_{dev})) + v_{\mathcal{M}}(\tau_x)F(t_{dev})]) \tag{26}$$

Then, notice that when the deviation starts, (i) the probability of occurrence of the mandatory scheme is $F(t_{dev}) = 0$, (ii) the biomass stock corresponds to the optimal conservation level, $S(t_{dev}) = S^*$ and (iii) the harvesting effort is, in any case, of $e_i(t_{dev}) = 1$. From the early definitions of $v_{FB}$ (Eq.(8)) and of $v_{\mathcal{M}}(\tau_x)$ (Eq.(17)), we thus obtain:

$$\frac{\partial \mathcal{V}^{dev}(\tau_x, t_{dev})}{\partial t_{dev}} \exp(\rho t_{dev}) = \pi(S^*)\,(e^* - 1) < 0 \text{ since } e^* < 1 \tag{27}$$

To conclude, we can say:

**Proposition 3.** *If a harvester decides to deviate from the announced conservation policy, he does not wait, i.e.* $t_{dev} = 0$*, he harvests at capacity,* $e_{dev}(t) = 1$*, and switches to* $e_{dev}(t) = e^{dev}$ *if condition (24) holds, before finally selecting the first best effort when the policy becomes mandatory. At date* $t_{dev}$*, his expectation on the evolution of the biomass are given by* $S_{dev}(t)$*, a decreasing path starting at* $S^*$ *which either reaches* $S^{dev}$ *in finite time or* $\bar{S}^{dev}$ *at infinite (depending on condition (24)). His expected gains from this deviation are:*

$$\mathcal{V}^{dev}(\tau_x) = \int_0^{+\infty} \exp(-\rho t)\,[\pi(S_{dev}(t))e_{dev}(t)\,(1 - F(t)) + v_{\mathcal{M}}(\tau_x)F(t)]\,dt \tag{28}$$

## 7. The capacity tax and the average delay

Moving to the last step of our analysis, we now consider the tax rate on excess capacity. It should be set, as further detailed, at a level ensuring it is credible to the deviator, and any deviation is deterred ex-ante. We provide a general characterization of such a tax rate, before studying its relationship with the average delay of the mandatory policy implementation.

### *7.1. Characterization*

Let us first focus on the deterrent property of the capacity taxation. We ask wether there exists a minimal tax rate, denoted $\tau_x^{inc}$, such that the individual return derived when no harvester deviate is equal to the expected return of a potential deviator, $\mathcal{V}^{dev}(\tau_x)$ (see Eq.(28)). As current profits under compliance (see Eq.(8)) are constant, the expected additional gain from deviation is given by:

$$\psi(\tau_x) = \mathcal{V}^{dev}(\tau_x) - \frac{1}{\rho}\pi\left(S^*\right)e^*. \tag{29}$$

We even observe that $\psi(\tau_x)$ is decreasing, since from Eqs. (28) and (17), it can be stated:

$$\psi'(\tau_x) = \left(\mathcal{V}^{dev}\right)'(\tau_x) = (v_{\mathcal{M}})'(\tau_x) \int_0^{+\infty} \exp(-\rho t) F(t) dt = -\tfrac{\delta}{\rho(\rho+\delta)} \pi(S^*)(1-e^*) < 0. \quad (30)$$

This means that the minimal tax rate solves $\psi(\tau_x^{inc}) = 0$, which yields:

$$\tau_x^{inc} = \tfrac{\rho(\rho+\delta)}{\delta} \int_0^{\infty} \exp(-\rho t) \underbrace{\left[\frac{\pi(S_{dev}(t))e_{dev}(t) - \pi(S^*)e^*}{\pi(S^*)(1-e^*)}\right]}_{R(t)} (1 - F(t))\, dt \quad (31)$$

In other words, it directly depends on the average ratio of the instantaneous deviation gain to the excess capacity tax base. Since $S_{dev}(t) < S^*$, $e_{dev}(t) \leq 1$ and $\pi(S)$ is decreasing, we notice:

$$0 \leq \frac{\pi(S_{dev}(t))e_{dev}(t) - \pi(S^*)e^*}{\pi(S^*)(1-e^*)} \leq \frac{\pi(S^*) - \pi(S^*)e^*}{\pi(S^*)(1-e^*)} = 1 \quad (32)$$

which implies that the minimal deterrent tax rate is smaller than $\frac{\rho}{\delta}$. Moreover, from our assumption on the occurrence of the mandatory policy $F(t)$, the average delay is given by $\frac{1}{\delta}$, meaning that the tax rate is always bounded from above by the the discount rate factored by the average delay. For instance, provided an average delay of 2 years and a discount factor of 5%, this tax rate will be lower than 10%.

We now examine the credibility condition. As already mentioned in section 4, credibility resolves itself into a mere budget condition in this framework. The intuition is simple. Any harvester, while considering his decision to deviate, has to be ensured the regulator will not rescind the mandatory tax. Otherwise, as a threat, it would loose the deterrent property defined above. The tax revenue generated by $\tau_x$ must therefore cover the cost of the secured return principle. Most importantly, this requirement must hold ex-ante, whatever the duration of the political process. Since he plans to act as described in proposition 3, any potential deviator expects the biomass to be given by $S_{dev}(t)$. As a consequence, we have to find a minimal tax rate, $\tau_x^m$, such that a mandatory policy starting in any state within $\left[\max\left\{S^{dev}, \bar{S}^{dev}\right\}, S^*\right]$, satisfies the budget requirement.

To begin with, let us initiate the mandatory policy at date $t_m$, with a biomass stock $S \in \left[\max\left\{S^{dev}, \bar{S}^{dev}\right\}, S^*\right]$. As planned, the regulator secures the returns of the harvester until the optimal conservation level is reached at date $t_m + T(S)$ (see remark 1), while collecting the capacity tax over the whole horizon. He thus does not run into a deficit if:

$$-n \int_{t_m}^{t_m+T(S)} \exp(\rho(t-t_m)\pi(S^*)e^* dt + n \int_{t_m}^{\infty} \exp(\rho(t-t_m)\pi(S^*)\left(1-e^*\right)\tau_x dt \geq 0, \quad (33)$$

which requires a minimal tax rate of:

$$\tau_x(S) = \frac{e^*}{1-e^*}\left(1 - \exp(-\rho T(S))\right). \quad (34)$$

Then, remark that this minimal tax rate does not even depend on the mandatory policy implementation starting date. The only variable of interest is $T(S)$, which is the delay necessary to restore the optimal conservation level by means of a moratorium. Since this delay is increasing with the level of depletion of the resource, it simply remains to set:

$$\tau_x^m = \tau_x \left( \max \left\{ S^{dev}, \bar{S}^{dev} \right\} \right) \tag{35}$$

in order to ensure the credibility of the policy for any time $t_m$ at which the mandatory policy starts. In other words, $\tau_x^m$ is either equal to $\tau_x \left( S^{dev} \right)$ or $\tau_x \left( \bar{S}^{dev} \right)$, depending whether the optimal deviation corresponds to some feasible MRAP to $S^{dev}$, or to the maximal effort with a smooth convergence to $\bar{S}^{dev}$ (see condition (24) and proposition 3). To summarize all these observations, we can say:

**Proposition 4.** *If, as depicted in section 3, the regulator threatens the harvesters with a mandatory regulation which features a tax rate $\tau_x = \max \left\{ \tau_x^{inc}, \tau_x^m \right\}$ on excess capacity, the optimal conservation level of biomass will be sustained. Such a tax rate deters any deviation, and is credible.*

*7.2. Impact of the average delay*

Let us now further examine the average delay of the occurrence of the mandatory policy, $\frac{1}{\delta}$. Indeed, understanding how $\delta$ relates to $\tau_x$ requires to study the way this average delay impacts the deviation. Proposition 3 clearly points out that two scenarii may occur: either $S_{dev}(t)$ converges to $\bar{S}^{dev}$ at a maximal harvesting level, or this path has a MRAP characterized by a convergence to $S^{dev}$ and an effort switch, in finite time, from 1 to $e^{dev}$. These scenarii depend whether $r \left( S^{dev} \right) \gtreqless q + \frac{(n-1)}{n} r(S^*)$ (see Eq.(24)). Moreover, observe from Eq.(22) that $S^{dev}$ depends on the average delay, with $\frac{dS^{dev}}{d(1/\delta)} > 0$ (see E). Since the biomass growth rate, $r(S)$, is decreasing it is now obvious that: for a short average delay, $\frac{1}{\delta} < \frac{1}{\bar{\bar{\delta}}}$, the deviator will choose a maximal harvesting strategy that converges to $\bar{S}^{dev}$, while for a longer delay $\frac{1}{\delta} > \frac{1}{\bar{\bar{\delta}}}$, he will care, in some sense, of conservation by adopting a MRAP path which contains a switching to some less aggressive harvesting behavior. The reader should nevertheless notice both scenarii only happen when $\lim_{\frac{1}{\delta} \to \infty} r(S^{dev}) < q + \frac{n-1}{n} r(S^*)$, which does not depend on the delay. In the opposite case, only the first scenario occurs like, for instance, in the example of the next section.

So let us first consider a short average delay, i.e. $\frac{1}{\delta} \leq \frac{1}{\bar{\bar{\delta}}}$. In this case, $S^{dev} \leq \bar{S}^{dev}$ where $\bar{S}^{dev}$ defines as a stationary state of:

$$\frac{\dot{S}(t)}{S(t)} = r(S(t)) - q \left( 1 + (n-1) e^* \right) \text{ with } S(0) = S^* \tag{36}$$

Since this motion does not depend on the delay, the same holds for the credible tax rate, $\tau_x^m$,(see Eqs.(34) and (35)). It is not the case for the deterrent tax rate, $\tau_x^{inc}$ (see Eq.(31)). Even if we know that $\forall t$, $e_{dev}(t) = 1$ and $S_{dev}(t)$ solves Eq. (36) meaning that $S_{dev}(t)$ is independent of the delay and converges to $\bar{S}^{dev}$, we have:

$$\frac{d\tau_x^{inc}}{d\delta} = -\tfrac{\rho^2}{\delta^2} \int_0^\infty \exp(-\rho t) R(t) \left( 1 - F(t) \right) dt + \tfrac{\rho(\rho+\delta)}{\delta} \int_0^\infty \exp(-\rho t) R(t) \tfrac{\partial(1-F(t))}{\partial \delta} dt \tag{37}$$

Furthermore, $\frac{\partial(1-F(t))}{\partial\delta} = -\delta\,(1-F(t))$, so it can be said, from Eq. (32), that $\frac{d\tau_x^{inc}}{d\delta} < 0$, or equivalently, that the deterrent tax rate $\tau_x^{inc}$ is increasing with the average delay of the policy. Finally, remember that the tax rate announced is given by $\tau_x = \max\{\tau_x^{inc}, \tau_x^m\}$. Thus we can state it is non-increasing with the average delay of the mandatory policy as long, of course, the latter remains small enough.

If the average delay is large enough, i.e. $\frac{1}{\delta} > \frac{1}{\bar{\delta}}$, then $S_{dev}(t)$ which solves Eq. (36) reaches $S^{dev} > \bar{S}^{dev}$ in finite time, which we denote $t(S^{dev})$. After this period, $e_{dev}(t)$ switches to $e^{dev}$, but $S_{dev}(t)$ and $\delta$ remain independent for $t < t(S^{dev})$. A first consequence is that $\tau_x^m$ now depends on the average delay, since the maximal time, $T(S^{dev})$, necessary to restore the biomass under the mandatory policy, depends on $S^{dev}$:

$$\frac{d\tau_x^m}{d(1/\delta)} = -\frac{e^*}{1-e^*}\rho\exp(-\rho T(S^{dev}))\,\frac{dT}{dS}\Big|_{S=S^{dev}}\frac{dS^{dev}}{d(1/\delta)} \tag{38}$$

Then remark that the time necessary to restore the biomass from $S < S^*$ to $S^*$ under an optimal (mandatory) policy, decreases with $S$, and that $\frac{dS^{dev}}{d(1/\delta)} > 0$ . Both imply that the tax rate which ensures the credibility of the policy decreases with the average delay of occurrence of the mandatory policy, $\frac{d\tau_x^m}{d(1/\delta)} > 0$. A second consequence is that the relationship between the deterrent tax rate, $\tau_x^{inc}$, and the delay, becomes less obvious. Indeed, both the switching time, $t(S^{dev})$, and the instantaneous profits after this switch, $\pi(S^{dev})e^{dev}$, depend on the delay. It can however be shown (see E) that the intuition which suggests that the deterrent tax rate is increasing with the delay is still relevant. To summarize all these observations, we can say:

**Proposition 5.** *If the expected delay of the implementation of a mandatory policy increases, then:*
*(i) the deterrent tax rate, $\tau_x^{inc}$, also increases because each deviator benefits from a larger average window within which there is an opportunity to benefit from the deviation;*
*(ii) the credible tax rate, $\tau_x^{inc}$, is constant for a low average delay $\frac{1}{\delta} \le \frac{1}{\bar{\delta}}$, while it increases for a large average delay since the maximal time, $T(S^{dev})$, to restore the biomass and to secure the returns of the harvesters increases;*
*(iii) by definition of the* max*, the tax announced by the regulator, $\tau_x = \max\{\tau_x^{inc}, \tau_x^m\}$, also increases.*

## 8. A illustration: the scallop fishery in the bay of Saint-Brieuc

We use a numerical example to illustrate our V-T policy[12]. In particular, we apply it to the case of the common scallop (*pecten maximus*) fishery, located in the Bay of Saint-Brieuc on the northern coast of Brittany (France). Apart from being the second largest scallop fishery in France, it is also, most remarkably, known to be one of the most regulated fishing industry. To begin with, first access is limited in two ways. A *numerus clausus* licence policy limits the number of boats to $n = 250$, while the fishery

[12]Detailed computations performed with Maple are available upon request.

only opens 45 minutes two days a week during the fishing season. Hence, the number of vessels is constant and the maximal fishing effort is clearly identified. Secondly, as access restrictions did not suffice to preserve the scallop population, the regulatory agency has added some command and control measures (harvesting quotas per vessel and mesh size restrictions). The purpose of this example is to point out that these costly additional command and control policies can be replaced by a V-T policy. Specifically, we suggest a set of capacity tax rates, depending on the average policy implementation delay, which ensures optimal conservation.

The data and the functional forms of this example are mainly borrowed from Frésard and Ropars-Collet [20]. We thus assume a logistic growth rate function $r(S) = \mu(1-S/K)$, with a unit profit per effort given by $\pi(S) = (pqS - c)$. The parameters values are summarized in Table 1.

| Parameter | Description | Value |
|---|---|---|
| $r$ | Intrinsic growth rate | 0.649 |
| $K$ | Carrying capacity | 54252 (tons) |
| $p$ | Ex-vessel unit price | 2000 (€ per ton) |
| $q$ | Catchability coefficient | $2.961 \times 10^{-3}$ |
| $c$ | Unit cost of fishing effort | 4746 (€ per boat) |
| $n$ | Number of vesselst | 250 |
| $\rho$ | Discount ratet | 0.05 |

Table 1: The scallop fishery in the Bay of Saint-Brieue

As in Frésard and Ropars-Collet [20], we choose a discount rate $\rho = 0.05$ and a number of players $n = 250$ (defined by the *numerus clausus*). But in their paper, the effort is counted in fishing hours per year, and not as a proportion of the maximal capacity. So, using the threshold that implies, de facto, the access regulation previously described, we set it to 42 hours. It corresponds to a season of seven months with 1.5 fishing hours per week, which we normalize to one so as to fit our model. Then, we adjust in consequence the unit effort cost, $c$, and the catchability coefficient, $q$. Under these assumptions, table 2 describes the first best stationary outcomes.

| Variable | Description | Value |
|---|---|---|
| $S^*$ | Optimal biomass stock | 25503 (tons) |
| $S_{min}$ | Minimal stock condition for positive profit | 801.418 (tons) |
| $nS^*qe^*$ | Total catch per season | 8779 (tons/year) |
| $e^*$ | Individual optimal effort | 0.465 |
| | Equivalent harvesting hours | 19.5 (hours) |
| $S^*qe^*$ | Individual catch per season | 35.1 (tons/year) |
| $\pi(S^*)e^*$ | Individual stationary profits | 67961.87 €/year |

Table 2: The first best stationnary conservation target

Table 2 clearly shows that access control is not sufficient to achieve the first best stationary level of biomass. The regulated number of fishing hours is twice the optimal one, and the *numerus clausus* set at $n = 250$ makes extraction possible at a rate larger than the maximal growth rate compatible with non negative profits, i.e. $n > \lceil r(S_{min})/q \rceil = 215$. This result confirms the current mandatory regulation actually mainly relies on the existence of non-transferable quotas and mesh control.

In order to understand how to set the capacity tax, let us first assume our voluntary mechanism is implemented and look at the potential deviation. From proposition 3, we know that two kinds of behaviours may occur depending whether the deviator has or not a sufficient fishing capacity to reach $S^{dev}(\delta)$ (see Eq.(24)). In the Saint-Brieuc case, this discussion is useless since:

$$\forall \delta,\ r\left(S^{dev}(\delta)\right) \geq r\left(S^{dev}(0)\right) \simeq 0.5142 > 0.3455 \simeq q + \tfrac{(n-1)}{n} r(S^*) \tag{39}$$

This means that the deviator always plan to harvest at full capacity during the deviation, i.e. $e_{dev}(t) = 1$ . Thus, his expectation on the evolution of the biomass is, under our specifications, given by:

$$S_{dev}(t) \simeq \frac{104975831200}{4137789.013 - 21501.65105 \exp\left(-0.1182344857t\right)}, \tag{40}$$

a path which converges to $\bar{S}^{dev} \simeq 25370.03$ tons. For a given random delay of the policy and an announced capacity tax $\tau_x$, the deviator knows that his instantaneous expected gains amount to:

$$v_{dev}(t, \delta, \tau_x) \simeq e^{-\delta t}\left(5.922 S_{dev}(t) - 4746\right) + \left(1 - e^{-\delta t}\right)\left(78318.24\tau_x - 67961.87\right) \tag{41}$$

For instance, figure 1 illustrates, for an average implementation delay of two years, such profits as a function of the capacity tax threat stringency. The black flat surface depicts the profit under compliance (i.e. at the first best conservation level).

We finally turn to characterizing the minimal capacity tax rate which credibly deters any deviation. If we consider the deterrent part, this consists in, referring for instance to figure 1, finding the level of tax rate such that the present value of the deviation expected instantaneous gain is equal to the present value of compliance, i.e.

$$\textstyle\int_0^\infty v_{dev}(t, \delta, \tau_x) e^{-0.05t} dt \simeq \frac{1}{0.05} 67961.87 \simeq 1359237 \tag{42}$$

As regards the scallop fishery in the Saint-Brieuc bay, the relation between the average policy delay and the capacity tax rate is described in table 3.

| Average delay (in years) | .5 | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 |
|---|---|---|---|---|---|---|---|---|---|---|
| Deterent capacity tax | .025 | .049 | .075 | .099 | .124 | .149 | .174 | 199 | .224 | .249 |

Table 3: Average policy delay and deterent capacity tax

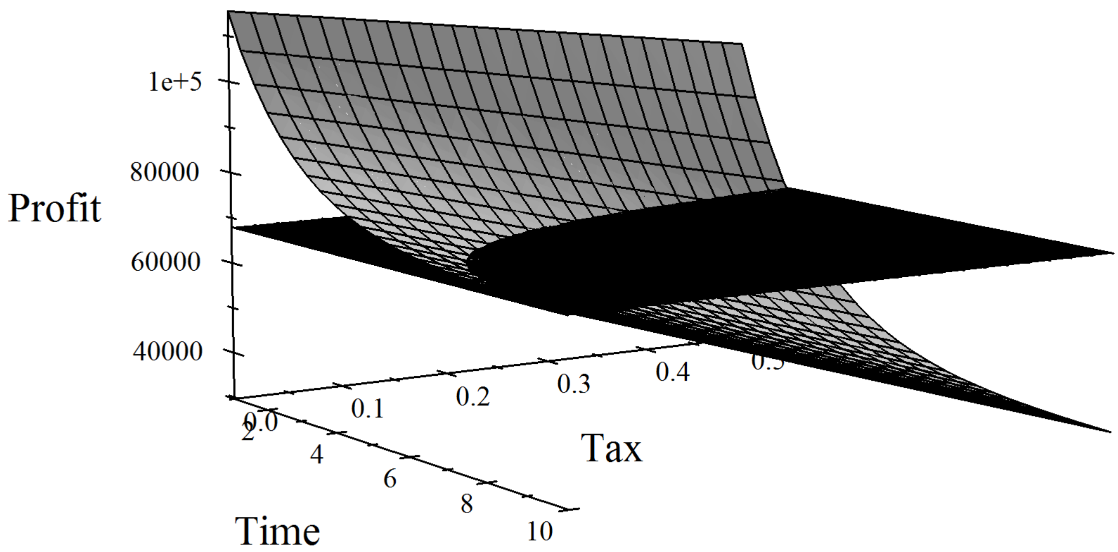


Figure 1: Instantaneous profit after deviation for an average policy delay of two years.

Finally, it simply remains to verify that these tax rates are also credible. This is not really a problem in our example. In fact, under the access restriction, the recovery of the biomass is quite fast, so that the length of the moratorium included in our mechanism is rather short. In other words, a very small long lasting capacity tax easily covers the short run spending to secure the harvesters' returns. In our example, this tax rate, $\tau_x^m$, is roughly .0007.

## 9. Concluding remarks

In this paper we have devised a voluntary conservation policy to manage fisheries, which relies on a mandatory tax scheme such that, when it is used as a threat, compliance yields higher expected profits than any deviation. Moreover, when enforced, the mandatory scheme credibly implements the first best and guarantees the first-best stationary profits to harvesters. The part of the mandatory policy that actually deters harvesters from deviating is a tax on excess capacity, $\tau_x = \max\{\tau_x^{inc}, \tau_x^m\}$, the level of which is shown to depend on the average enforcement delay. Specifically, we find that $1/\delta$ impacts : (i) the deterrent level of tax-rate, $\tau_x^{inc}$, since the average delay always influences the expected gains of deviation, via the expected length of the deviation window, and indirectly, via the deviator extraction behavior during the deviation, (ii) the credible tax rate, $\tau_x^{inc}$, i.e. the level of tax rate such that the mandatory policy is ensured to be budget balanced, via the recovery costs' upper bound. Nevertheless, when this average delay is short enough, the credible tax rate may be constant. The ranking of $\tau_x^{inc}$ and $\tau_x^m$ eventually depends on the population biological dynamics, the discount rate, the unit price of catch and the cost of effort. In the case of the scallop fishery in the bay of Saint-Brieuc, the deterrent capacity tax is greater than the credible one, even for small average delays.

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# Appendix

## A. Proof of Lemma 1

**Existence** is immediate. Since $\pi(S_{\min}) = 0$, we know from the definition of $\phi_{FB}(S)$ (see Eq.(6)) that $\phi_{FB}(S_{\min}) = -\pi'(S_{\min})r(S_{\min}) < 0$ (remember that $\pi'(S) > 0$ and $r(S_{\min}) > 0$) while $\phi_{FB}(K) = \left(\frac{\rho}{S} - r'(K)\right)\pi(K) > 0$ since $r(K) = 0$ and $r'(S) < 0$. The result then follow from the continuity of $\phi_{FB}(S)$.

**Uniqueness** relies on the idea that if $(\phi_{FB})'(S)$ maintains its sign at each solution, then this solution is unique. So, let us first observe that:

$$(\phi_{FB})'(S) = \left(-\frac{\rho}{S^2} - r"(S)\right)\pi(S) + \left(\frac{\rho}{S} - r'(S)\right)\pi'(S) - \pi"(S)r(S) - \pi'(S)r'(S) \tag{43}$$

If we evaluate this derivative at a solution $S^*$ of Eq.(6), we know that $\frac{\rho}{S} = r'(S^*) + \frac{\pi'(S^*)}{\pi(S^*)}r(S^*)$ and we obtain, after computation, that:

$$(\phi_{FB})'(S^*) = \underbrace{-\left(\pi'(S^*)r'(S^*) + r'(S^*)\frac{\pi(S^*)}{S^*} + r"(S^*)\pi(S^*)\right)}_{=A} - r(S^*)\underbrace{\left(\frac{\pi'(S^*)}{S^*} - \frac{(\pi'(S^*))^2}{\pi(S^*)} + \pi"(S^*)\right)}_{=B} \tag{44}$$

Since we have assumed that $\forall S \in (S_{\min}, K)$, $\pi(S), \pi'(S) > 0$, $r'(S), r"(S) < 0$, we can claim that $A > 0$. Now let us observe that:

$$B = \frac{1}{S^*\pi(S^*)}\left((\pi'(S^*) + \pi"(S^*)S^*)\pi(S^*) - S^*(\pi'(S^*))^2\right) = \frac{\pi(S^*)}{S^*}\frac{d}{dS}(\varepsilon_\pi(S^*)) < 0 \tag{45}$$

In other words, that $B$ is negative since the elasticity $\varepsilon_\pi(S)$ of the profit function decreases on $(S_{\min}, K)$. We conclude that $(\phi^c)'(S^*) > 0$, meaning that the solution to $\phi_{FB}(S) = 0$ is unique.

**Sign of $\phi_{FB}(K)$**. From the previous property, it is obvious that $\forall S \in [S_{\min}, K]$ if $S < S^*$ (resp. $>$) then $\phi_{FB}(S) < 0$ (resp. $>$).

## B. Proof of Proposition 1

Following Hartl and Feichtinger ([28]: Theorem 3.1) and lemma 1, it remains to verify that:

**The biomass path is feasible**. This means that the control $e^{FB}(S) \in [0,1]$. This is typically the case before the steady state is reached because $e^{FB}(S)$ is, in this case, either 0 or 1. It thus remains to verify that $e^* \in [0,1]$. But remember that the specis is endangered and the growth rate is decreasing, i.e. $r(S^*) < r(S_{\min}) < nq$, hence $e^* = \frac{r(S^*)}{nq} \in (0,1)$.

**The transversality condition is verified**. This one is given by $\lim_{t\to+\infty} e^{-\rho t}\int_{S(t)}^{S^*}\left(-\frac{\pi(\sigma)}{q\sigma}\right)d\sigma \geq 0$, for any feasible trajectory $S(t)$. Let us first observe that we can, by the the non-negativity condition of the instantaneous profit, restrict the set of feasible paths to those belonging to $[S_{\min}, K]$. On this set, the quantity $\left(-\frac{\pi(S)}{qS}\right)$ is, by continuity, bounded. It follows that any path $S(t) \in [S_{\min}, K]$ is such that $\int_{S(t)}^{S^*} \left(-\frac{\pi(\sigma)}{q\sigma}\right) d\sigma$ is bounded for all $t$. We can therefore claim that $\lim_{t\to+\infty} e^{-\delta t} \int_{S(t)}^{S^*} \left(-\frac{\pi(\sigma)}{q\sigma}\right) d\sigma = 0$.

## C. Proof of Lemma 2

**Existence**. Since $\pi(S_{\min}) = 0$, Eq.(22) says that $\phi_{dev}(S_{\min}) = -\pi'(S_{\min}) \left(r\left(S_{\min}\right) - (n-1)\, qe^*\right)$. Now remember, from Eq.(7), that $qe^* = \frac{r(S^*)}{n}$ and that $r'(S) < 0$. This implies that $\left(r\left(S_{\min}\right) - (n-1)\, qe^*\right) > \frac{1}{n} r(S^*) > 0$ so that $\phi_{dev}(S_{\min}) < 0$. Moreover, from the early definition of $S^*$ (see Eq.(6)), $\phi_{dev}(S^*) = \pi(S^*)\frac{\delta}{S^*} + \pi'(S^*)\,(n-1)\, qe^*$. This quantity is positive since for $S > S_{\min}$, we know that $\pi(S), \pi'(S) > 0$. Existence follows by continuity of $\phi_{dev}$.

**Uniqueness** is obtained as in the proof of Lemma 1. So let us first observe that:

$$\left(\phi_{dev}\right)'(S) = \left(-\frac{\rho+\delta}{S^2} - r''(S)\right)\pi(S) + \left(\frac{\rho+\delta}{S} - r'(S)\right)\pi'(S) - \pi''(S)\left(r\left(S\right) - (n-1)\, qe^*\right) - \pi'(S)r'(S) \tag{46}$$

If we now introduce Eq.(22), we obtain, after computation, that:

$$\begin{aligned}\left(\phi_{dev}\right)'\left(S^{dev}\right) = &-\underbrace{\left(\pi'(S^{dev})r'(S^{dev}) + r'(S^{dev})\frac{\pi(S^{dev})}{S^{dev}} + r''(S^{dev})\pi(S^{dev})\right)}_{=A'} \\ &-\left(r\left(S^{dev}\right) - (n-1)\, qe^*\right)\underbrace{\left(\frac{\pi'(S^{dev})}{S^{dev}} - \frac{\left(\pi'(S^{dev})\right)^2}{\pi(S^{dev})} + \pi''\left(S^{dev}\right)\right)}_{=B'}\end{aligned} \tag{47}$$

It remains to observe, since $r'(S) < 0$, that $r\left(S^{dev}\right) - (n-1)\, qe^* > r\left(S^*\right) - (n-1)\, qe^* = \frac{r(S^*)}{n} > 0$ and to use similar arguments as in in the proof of Lemma 1 in order to sign $A'$ and $B'$.

**The sign of $\phi_{dev}(S)$** follows from the two previous results.

## D. Proof of Proposition 3

*Case 1* : $r\left(S^{dev}\right) - \frac{(n-1)}{n} r(S^*) \leq q$

In this case, there exists a unique effort $e^{dev} \in (e^*, 1]$ which sustains $S^{dev}$ as a steady state. So, following Hartl and Feichtinger ([28]: Theorem 3.1) and from Lemma 2, the MRAP approach applies if the following transversality condition $\lim_{t\to+\infty} e^{-\rho t} \int_{S(t)}^{S^*} (1 - F(t)) \left(-\frac{\pi(\sigma)}{q\sigma}\right) d\sigma \geq 0$ is met. Since $(1 - F(t)) \in [0, 1]$, this is a straightforward consequence of the proof of proposition 1.

*Case 2* : $r\left(S^{dev}\right) - \frac{(n-1)}{n} r(S^*) > q$

In this case, the dynamics of $S$ (see Eq.(21)) associated to an effort $e(t) = 1$ admits a steady state $\bar{S}^{dev}$ given by $r\left(\bar{S}^{dev}\right) = q + \frac{(n-1)}{n} r(S^*)$ which belongs to $\left(S^{dev}, S^*\right)$ since $r'(S) < 0$. Moreover, let us denote by $\bar{S}^{dev}(t)$ the biomass path that solves Eq.(21) with $e(t) = 1$. It remains to show that this path is optimal. So let us take any path $S(t)$ starting at $S^*$ at $t = t_{dev}$ and which satisfies the feasibility condition given by the following differential inclusion:

$$\dot{S}(t) \in \left[\left(r(S(t)) - \left(1 + (n-1)\, e^*\right)\right) S(t), \left(r(S(t)) - (n-1)\, e^*\right) S(t)\right] \tag{48}$$

Let us also observe from the dynamics of the biomass (Eq.(21)) that:

$$e(t)dt = \left(\frac{r(S(t))}{q} - (n-1)e^*\right) dt - \frac{1}{qS(t)} dS \tag{49}$$

In this case for any admisible path $S(t)$ and any finite $T > t_{dev}$, the value of the objective (Eq.20) can be viewed as a line integral. More precisely:

$$\begin{aligned} J(S(\cdot),T) &= \int_{t_{dev}}^{T} \exp(-(\rho+\delta)t)\pi(S(t))e(t)dt \\ &= \int_S \left[\underbrace{\exp(-(\rho+\delta)t)\pi(S)\left(\tfrac{r(S)}{q}-(n-1)e^*\right)}_{=M(S,t)}\right]dt + \left[\underbrace{-\exp(-(\rho+\delta)t)\tfrac{\pi(S)}{qS}}_{=N(S,t)}\right]dS \end{aligned}$$

Now, let us compute $\Delta(T) = J(\bar{S}^{dev}(\cdot),T) - J(S(\cdot),T)$ for all admissible path $S(\cdot)$. From Anaya et al. ([4] remark 2.1), we can say that, for an initial condition given by $S^*$, $\bar{S}^{dev}(t)$ is the lowerst bound of the paths that verifies the differential inclusion given by Eq.(48). Since $S(\cdot) \neq \bar{S}^{dev}(\cdot)$, this means that we only observe two typical configurations: either $S(t) > \bar{S}^{dev}(t)$ on an open subinterval of $[t_{dev}, T]$ or $S(t) > \bar{S}^{dev}(t)$ for $(t', T]$ (see figure 1).

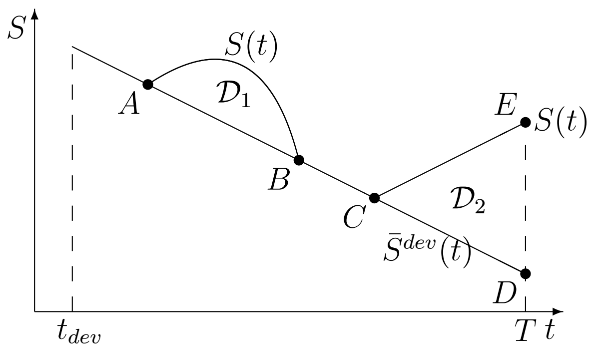


Figure 2: Paths of $\bar{S}^{dev}(t)$ and $S(t)$

So even if configuration $ABA$ can occur several time, we can say that $\Delta(T)$ is typically of the form of:

$$\begin{aligned} \Delta(T) = &\left(\oint_{ABA} M(S,t)dt + N(S,t)dS\right) + \left(\oint_{CDEC} M(S,t)dt + N(S,t)dS\right) \\ &- \left(\oint_{DE} M(S,t)dt + N(S,t)dS\right) \end{aligned} \tag{50}$$

Moreover from Green's theorem, we know that:

$$\begin{cases} \oint_{ABA} M(S,t)dt + N(S,t)dS = \iint_{\mathcal{D}_1} \left(\frac{\partial N}{\partial t}(S,t) - \frac{\partial M}{\partial S}(S,t)\right) dSdt \\ \oint_{CDEC} M(S,t)dt + N(S,t)dS = \iint_{\mathcal{D}_2} \left(\frac{\partial N}{\partial t}(S,t) - \frac{\partial M}{\partial S}(S,t)\right) dSdt \end{cases} \tag{51}$$

and by computation, we can say:

$$\left(\frac{\partial N}{\partial t}(S,t) - \frac{\partial M}{\partial S}(S,t)\right) = \frac{\exp(-(\rho+\delta)t)}{q}\phi_{dev}(S) \tag{52}$$

Since any $S$ in $\mathcal{D}_1, \mathcal{D}_2$ is larger than $S^{dev}$, we can say, by lemma 2, that the two first line integrals of Eq. (50) are strictly positive. Moreover, for the last one $dt = 0$, it follows that:

$$\Delta(T) > -\left(\int_{\bar{S}^{dev}(T)}^{S(T)} N(S,t)dS\right) = \exp(-(\rho+\delta)T)\int_{S(T)}^{\bar{S}^{dev}(T)} \frac{\pi(S)}{qS}dS \tag{53}$$

Finally, from case 1, we know that $\int_{S(T)}^{\bar{S}^{dev}(T)} \frac{\pi(S)}{qS}dS$ is bounded for any admissible path belonging to $[S_{\min}, K]$, so that $\lim_{T\to\infty} \Delta(T) > 0$ which shows that $\bar{S}^{dev}(t)$ is an optimal solution.

## E. Delay and taxation

Delay and deviation:

(i) $S^{dev}$ *increases with the average delay, i.e.* $\dfrac{dS^{dev}}{d\left(1/\delta\right)} > 0$. This follows from the application of the implicite function theorem to Eq.(22) since a direct computation shows that $\left.\frac{\partial\phi_{dev}}{\partial\delta}\right|_{S=S^{dev}} = \frac{\pi(S^{dev})}{S^{dev}} > 0$. and from C, we know that $\left.\frac{\partial\phi_{dev}}{\partial S}\right|_{S=S^{dev}} > 0$. It follows that $\frac{dS^{dev}}{d\delta} < 0$ or equivalently that $\frac{dS^{dev}}{d(1/\delta)} > 0$.

(ii) $S_{dev}(t)$ *is independant from* $\delta$ *for all* $t$ *or all* $t < t(S^{dev})$ *depending whenever* $\frac{1}{\delta} \lesseqgtr \frac{1}{\bar{\delta}}$. In fact $S_{dev}(t)$ solves Eq.(36) for $\forall t$ or $\forall t < t(S^{dev})$ depending whenever $\frac{1}{\delta} \lesseqgtr \frac{1}{\bar{\delta}}$ and Eq.(36) is independent of $\delta$, hence $\frac{\partial S_{dev}(t)}{\partial\delta} = 0$ $\forall t$ or $\forall t < t(S^{dev})$ respectively.

(iii) *For* $\frac{1}{\delta} > \frac{1}{\bar{\delta}}$, *we have* $\frac{dt(S^{dev})}{dS^{dev}} = \left(r(S^{dev}) - q\left(n-1\right)e^{*} - q\right)^{-1} S^{dev}$. In fact $t(S^{dev})$ is given by $S^{dev} = S_{dev}(t)$ and $S_{dev}(t)$ solves Eq.(36) solves. This implies that $dS^{dev} = \left.\dot{S}(t)\right|_{S^{dev}} dt$. The result follows from the definition of the dymanics (Eq.(36)).

Properties of $R(t) = \frac{\pi(S_{dev}(t))e_{dev}(t) - \pi(S^{*})e^{*}}{\pi(S^{*})(1-e^{*})}$

(iv) $R(t) \in [0,1]$ (see Eq. (32)

(v) $\dfrac{\partial R(t)}{\partial\delta} = 0$ *for* $\forall t$ or $\forall t < t(S^{dev})$ *depending whenever* $\frac{1}{\delta} \lesseqgtr \frac{1}{\bar{\delta}}$. This result follows from (ii) and the fact that $e_{dev}(t) = 1$ in both cases.

(vi) *For* $\frac{1}{\delta} > \frac{1}{\bar{\delta}}$ *and* $\forall t > t(S^{dev})$, $\dfrac{\partial R(t)}{\partial\delta} = \dfrac{\left(\rho+\delta\right)\pi\left(S^{dev}\right)}{qS^{dev}\pi(S^{*})(1-e^{*})}\dfrac{dS^{dev}}{d\delta}$. In fact, let us first observe that for $\forall t > t(S^{dev})$, $S_{dev}(t) = S^{dev}$ and $e_{dev}(t) = e^{dev}$, so that $\frac{\partial R(t)}{\partial\delta} = \frac{1}{\pi(S^{*})(1-e^{*})}\frac{d\pi(S^{dev})e^{dev}}{d\delta}$. Moreover using the definition of $e^{dev}$ (see Eq.(23)), we can say that:

$$\frac{d\pi(S^{dev})e^{dev}}{d\delta} = \frac{dS^{dev}}{d\delta}\frac{1}{q}\left(\pi'\left(S^{dev}\right)\left(r(S^{dev} - q\left(n-1\right)e^{*}\right) + \pi\left(S^{dev}\right)r'(S^{dev})\right)$$

and from the definition of $S^{dev}$ (see Eq. 22), we conclude that $\dfrac{d\pi(S^{dev})e^{dev}}{d\delta} = \frac{(\rho+\delta)}{q}\frac{\pi\left(S^{dev}\right)}{S^{dev}}\dfrac{dS^{dev}}{d\delta}$

Deterrent tax rate and large delay

From Eq.(31), and point (v), we can say that:

$$\frac{d\tau_x^{inc}}{d\delta} = -\frac{\rho^2}{\delta^2}\int_0^{\infty} R(t)\exp(-\left(\rho+\delta\right)t)dt$$

$$+\frac{\rho(\rho+\delta)}{\delta}\left(\int_0^{t(S^{dev})} R(t)(-t)\exp(-\left(\rho+\delta\right)t)dt + \frac{dt(S^{dev})}{d\delta}\left(R(t)\exp(-\left(\rho+\delta\right)t)\right)_{t=t(S^{dev})^-}\right)$$

$$\frac{\rho(\rho+\delta)}{\delta}\left(\int_{t(S^{dev})}^{\infty}\left(\frac{\partial R(t)}{\partial\delta} - tR(t)\right)\exp(-\left(\rho+\delta\right)t)dt - \frac{dt(S^{dev})}{d\delta}\left(R(t)\exp(-\left(\rho+\delta\right)t)\right)_{t=t(S^{dev})^+}\right)$$

After simplifications by using our previous observations (especially point (vi), we get:

$$\frac{d\tau_x^{inc}}{d\delta} = \underbrace{-\frac{\rho^2}{\delta^2}\int_0^{\infty} R(t)\exp(-\left(\rho+\delta\right)t)dt - \frac{\rho(\rho+\delta)}{\delta}\int_0^{\infty} tR(t)\exp(-\left(\rho+\delta\right)t)dt}_{\leq 0 \text{ since } R(t)\in[0,1]}$$

$$+\frac{\rho(\rho+\delta)}{\delta}\underbrace{\left(\begin{array}{c}\dfrac{dt(S^{dev})}{dS^{dev}}\dfrac{dS^{dev}}{d\delta}\exp(-\left(\rho+\delta\right)t(S^{dev}))\dfrac{\pi(S^{dev})\left(1-e^{dev}\right)}{\pi(S^{*})(1-e^{*})} \\ +\dfrac{\left(\rho+\delta\right)\pi\left(S^{dev}\right)}{qS^{dev}\pi(S^{*})(1-e^{*})}\dfrac{dS^{dev}}{d\delta}\displaystyle\int_{t(S^{dev})}^{\infty}\exp(-\left(\rho+\delta\right)t)dt\end{array}\right)}_{A}$$

Moreover, by rearranging and using point (iii), $A$ can be written as:

$$A = \frac{dt(S^{dev})}{dS^{dev}} \frac{dS^{dev}}{d\delta} \frac{\exp(-(\rho+\delta)\,t(S^{dev}))\pi(S^{dev})}{q\pi(S^{*})(1-e^{*})} \left(q - qe^{dev} + r(S^{dev}) - q\,(n-1)\,e^{*} - q\right) = 0$$

since by construction $e^{dev}$ equates $\frac{\dot{S}}{S} = 0$ in Eq.(36). We can therefore conclude that $\tau_x^{inc}$ increases with the average delay $\frac{1}{\delta}$.