When Should the Regulator Be Left Alone in the Commons?

How Fishing Cooperatives Can Help Ameliorate Inefficiencies

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March 23, 2023

Abstract

This paper examines a common-pool resource where quotas and fines are set by a regulator, an artisanal organization (cooperative), or both. We analyze the interaction between these two regulatory agencies under a flexible policy regime, where quotas and fines can be revised across periods, and under an inflexible policy regime, where they cannot. We show that inefficiencies arise in the inflexible regime, but they are reduced when the two agencies coexist. We then extend our model to a setting where regulator and artisanal organization have misaligned preferences, demonstrating that the artisanal organization may be preferred when environmental damages are low, but the regulator may be preferable otherwise.

Keywords: Common-pool resource, regulation, artisanal organization, flexible policy, inflexible policy, inefficiencies.

JEL classification: H23, L13, Q50.

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1 Introduction

Fishing cooperatives and Territorial Use Rights for Fishing (TURF) programs have received more attention in the last decades, suggesting that their coexistence with a regulator can help the latter better protect the fishing ground or, generally, any other common pool resource. We seek to understand the effect of having two regulatory agencies (any form of artisanal organization and the regulator), identifying in which contexts having only one of the agencies managing the resource is socially optimal and in which cases, instead, having both agencies may be preferable. In the US, for instance, the National Oceanic and Atmospheric Administration (NOAA) coexists with at least five cooperatives (i.e., PCC & HSCP, Pollock mothership, and Chignik salmon, among others). In Norway, the Institute of Marine Research coexists with the Norwegian Fishermen's Sales Organization; and in Japan, the Ministry of Agriculture, Forestry and Fisheries coexists with around 456 fishing cooperative associations (FCAs) as reported by Uchida and Makino (2008).

Our model considers a common pool resource (CPR) able to regenerate across periods and two firms exploiting it in each period. We study the effect of only having a regulator (denoted as R) setting the aggregate allowable quota and fines; an artisanal organization alone, such as cooperatives and TURF programs, deciding individual quotas and fines to each fisherman (which we denote as AO); or both regulatory agencies being simultaneously active (B). This setting characterizes agencies exhibiting different abilities to observe appropriations levels. For instance, AOs closely work with fishermen, thus having access to more accurate information about their appropriations; whereas the R often works less closely with them.

As a benchmark, we first analyze a setting where R and AO exhibit the same objective function and they can easily revise their policies across periods ("flexible" policy regime), showing that no inefficiencies arise under any regulatory setting. Intuitively, our result indicates that the CPR can be efficiently regulated by either agent —R, AO, or B— as they all induce the same (first best) appropriation levels in each period. However, when regulatory agencies cannot adjust quotas and fines across periods ("inflexible" policy regime), we demonstrate that inefficiencies arise, since they do not induce socially optimal appropriations in each period. Intuitively, these agencies have a single policy tool to use across all periods, setting a linear combination of the quotas they would have set in the first- and second-period under a flexible policy regime.

We measure these inefficiencies as the difference in equilibrium appropriation levels between the inflexible (second best) and flexible (first best) regime. First, we show that no regulatory agency can, on its own, fully internalize the externalities that fishermen impose on each other in every period, implying that the inflexible regime, despite being welfare improving relative to no regulation, gives rise to *regulatory* inefficiencies, as they arise because regulatory agencies cannot revise their quotas/fines across periods. Our results not only apply to underdeveloped countries suffering from slow policy revisions, but also to countries where fishing quotas are regularly revised every year (such as total allowable catch in the EU) because, as suggested by non-profit organizations, climate change and natural disasters may produce sudden changes in the available stock, requiring more frequent adjustments in the allowable catches; see Marine Stewardship Council (2021).

When both agencies are present, however, we show that regulatory inefficiencies are minimized in every period, because one agency offsets the lack (excess) of stringency in the quotas set by the other agency in the first (second) period, respectively. In addition, we identify that, when a single agency is present, the R generally produces more inefficiencies than the AO does. Overall, our results suggest that, when agencies exhibit similar objectives, the AO's presence is unambiguously welfare improving, giving rise to smaller inefficiencies when operating alone, or helping reduce the R's inefficiencies due to the inflexible policy regime. Alternatively, this finding entails that, if the R's administrative costs are higher than the AO's, it should refrain from operating in CPRs when both agencies have similar objective functions, letting the AO do "all the work," especially in settings where the R cannot easily revise quotas and fines across periods. This is the case, for instance, of CPRs in Vietnam, Indonesia, or Sri Lanka where policies, despite being often updated, are rarely monitored; as reported in Atapattu (1987), Harkes and Novaczek (2002), Lai (2008), and Quynh et al. (2017). In contrast, CPRs in countries such as Japan or Chile, where quotas are often revised and closely monitored, would be closer to a flexible regime; as described in Cancino et al. (2007). In this policy regime, either agency can, on its own, induce socially optimal appropriation levels, not giving rise to inefficiencies. As a result, only one agency should manage the resource, choosing the agency with the lowest administrative costs.

As an extension, we examine scenarios where agencies have misaligned preferences, which can arise when the R considers the biodiversity loss produced by appropriations while the AO does not.[1] This modeling strategy allows us to study how regulatory inefficiencies are affected by the preference misalignment between R and AO. We show that, in this context, all agencies produce inefficiencies, including when both are active. In particular, we find that R and AO yield an underexploitation of the CPR, while the B entails an overexploitation for most settings. This result entails that, when agencies have asymmetric objectives, society faces a trade-off: either allow for the resource to be underexploited given the management of only one agency, or allow for it to be overexploited when both agencies simultaneously manage the resource. We then rank these inefficiencies, showing that the AO (B) induces the smallest underexploitation (overexploitation) of the resource when biodiversity loss is low, but R (B) is preferred when it is high.

Faster regeneration rates emphasize the above inefficiencies (both under- and overexploitation), particularly those from R, making its role welfare reducing under most parameter values. This case includes pelagics, such as Bigeye scad, Pacific herring or Sockeye salmon, which regenerate rapidly. In contrast, when regeneration rates are slow, our findings indicate that the R becomes socially preferred in more settings, which applies to mollusks, the Pacific ocean perch, or the Sablefish.[2]

Related literature. Since Hardin (1968), several studies have studied socially excessive ex-

[1] Alternatively, agents could exhibit different objective functions if the administrative costs from policy implementation (monitoring quota and setting fines) differs. If these costs are fixed (unaffected by first- or second-period appropriation), equilibrium results would be unaffected. However, if administrative costs are variable in aggregate appropriation, equilibrium results would differ from those in our base model.

[2] For details about other fish species, their growth rates and maturity, see Froese and Pauly (2021).

ploitation in CPRs.[3] Within the CPR literature, our study fits into the articles comparing two common policies to regulate CPRs —individual transferable quotas (ITQ) and collective right for fishing (TURF)— such as Boyce (2000), Danielsson (2000), Cancino et al. (2007), Arnason (2009), Zhou and Segerson (2016), and Isaksen and Richter (2019). However, we analyze equilibrium appropriation when different agencies manage the resource, allowing for flexible and inflexible policy regimes, and also letting R and AO exhibit different objective functions. Zhou and Segerson (2016) also analyzes CPR managements under individual quotas, with and without trading, and under collective quotas, where effort choices are decentralized or centralized; seeking to identify which setting yields the highest profits. While we do not consider transferable quotas, we evaluate whether the coexistence of regulatory agencies attenuates inefficiencies or, instead, augments them under certain contexts; and how our results are affected by the difference in agencies' objectives. Kotchen and Segerson (2019) also examines how different group policies can lead firms to behave closer to the social optimum, thus internalizing an externality they impose on third agents. Our paper considers one of their group policies, the "Proportional Tax with Allowable Group Limit," where the tax is paid only when aggregate appropriation exceeds a quota, but this tax is designed to help firms internalize an externality that they only impose on third agents (consumers), while we allow for the externality to affect both consumers and firms exploiting the resource.

Several studies examine the impact of different tax systems in fisheries where firms typically exceed their quotas. Mason and Polasky (1994), for instance, examine strategic overexploitation by incumbents operating in a CPR, seeking to deter entry of new competitors, showing that such overexploitation is more likely to arise when the CPR's stock is abundant. Chavez and Salgado (2005) develop a static model where every fisherman independently chooses its appropriation, as opposed to our setting, which helps identify intertemporal effects and collective decisions such as quotas or fines; and Costello and Kaffine (2008) examine how uncertainty in property rights, or the presence of minimum sustainability requirements, affect the CPR exploitation. In the case of TURFs, Villena and Chavez (2005) study a static game of norm compliance involving monitoring and penalty strategies under a regime of CPR exploitation. They study whether fishing communities with no tradition in cooperative management were able to achieve an appropriate level of compliance using a simultaneous game without a regulator.[4]

Other related papers include Huang and Smith (2014), which empirically estimates the CPRs inefficiencies comparing current and socially optimal exploitation paths; or Cash et al. (2006), which argues that institutions with different hierarchies (such as the R and AO) may be beneficial for fishermen at coordinating their decisions; or Segerson (1988), which analyzes the regulation of non-point source pollution when the social planner can only observe aggregate pollution, and shows that efficient pollution can be achieved. We similarly demonstrate that, when the R only observes the CPR's aggregate exploitation, an efficient appropriation can be induced. However, we

[3] Examples include how firms react to different penalties from regulators, as in Anderson and Lee (1986) and Charles et al. (1999); and how illegal catching impacts on quota decisions, in Milliman (1986). For a detailed related literature, see Faysse (2005).

[4] For a comprehensive review on applications of game theory to fisheries, see Hannesson (2011).

also explore how regulation is affected when an AO is also present, when agents cannot revise their policies in different periods, and when they exhibit different objective functions. As a result, we can identify in which contexts inefficiencies are minimized by having one regulatory agency alone, or both, actively present in the resource.

Section 2 describes the model and the following solves for equilibrium appropriation in the absence of regulation, as a benchmark. Section 4 (5) then introduces flexible (inflexible) regulation, and section 6 evaluates the appropriation inefficiencies that each agency (R, AO, or B) generates, and ranks these inefficiencies. Section 7 extends our previous results allowing for R and AO to exhibit different objective functions, and section 8 concludes.

2 Model

Consider a CPR exploited by two fishermen, i and j, during two periods. The initial stock of the CPR is exogenously given and denoted by θ, which is strictly positive. Each fisherman extracts an amount $e_k \in [0,1]$ where $k = \{i,j\}$. The market price is given, and normalized to 1, and fisherman i's first-period extraction cost is

$$c^1(e_i, e_j, \theta) = \frac{e_i(e_i + e_j)}{\theta}$$

where $j \neq i$, which is symmetric across fisherman.[5] Therefore, the marginal extraction cost is $\frac{2e_i+e_j}{\theta}$, which is increasing in fisherman i's own appropriation, e_i, in its rival's appropriation, e_j (cost externality), and decreasing in the abundance of the stock, θ.

First period. Fisherman i's profits when facing the artisanal organization AO (regulator, R) are,

$$\pi_i^{1,AO} = e_i - \frac{e_i(e_i + e_j)}{\theta} - \alpha \left[f_i\left(e_i - \bar{e}_i\right) - f_j\left(e_j - \bar{e}_j\right)\right]$$

and

$$\pi_i^{1,R} = e_i - \frac{e_i(e_i + e_j)}{\theta} - \beta \frac{F}{2}(e_i + e_j - \hat{e})$$

where α (β) denotes the probability that fisherman i is monitored by the AO (R, respectively), and α, $\beta \in [0,1]$. Fisherman i is found liable by the AO if and only if his extraction exceeds his assigned quota, $e_i > \bar{e}_i$, entailing a penalty $f_i \geq 0$. Otherwise, he faces no penalty or subsidy. In addition, fisherman i receives the penalty paid by fisherman j since fines are revenue neutral.[6]

Similarly, he is found liable by the R if and only if aggregate extraction exceeds the quota, $e_i + e_j > \hat{e}$, each fisherman paying a penalty $F/2$. If fisherman i faces both the AO and R, his first-period profit is

$$\pi_i^{1,B} = \pi_i^{1,AO} - \beta \frac{F}{2}(e_i + e_j - \hat{e})$$

[5] We restrict our analysis to symmetric costs since it helps us focus on the dynamics between different regulatory agencies

[6] The above profit function allows for the possibility that fisherman i's extraction falls below his assigned quota, $e_i < \bar{e}_i$, thus receiving a subsidy. However, we show that, in equilibrium, this does not occur and, instead, fisherman i chooses e_i so that $e_i \geq \bar{e}_i$. A similar argument applies to the penalty paid by fisherman j.

where superscript B denotes both regulatory agencies. This penalty setting characterizes the difference between an AO, which maintains a close interaction with fishermen, and a R that usually observes aggregate appropriations.

Second period. In the second period, fisherman i's extraction cost becomes

$$c^2(x_i, x_j, \theta, E) = \frac{x_i(x_i + x_j)}{\theta(1+g) - E}$$

where $E \equiv e_i + e_j$ denotes first-period aggregate appropriation, and x_i is fisherman i's second-period extraction. Note that the available stock at the beginning of the second period is $\theta(1+g) - E$, and $g \in \left[0, \frac{E}{\theta}\right]$ represents the growth rate of the initial stock. When $g = 0$, the initial stock θ does not regenerate, implying that fishermen face a stock $\theta - E$ at the beginning of the second period. In contrast, when $g = \frac{E}{\theta}$, the stock is fully recovered, so the initial stock θ is the same at the beginning of the second period.[7] Hence, second-period profits when facing the AO (R) are

$$\pi_i^{2,AO} = x_i - \frac{x_i(x_i + x_j)}{\theta(1+g) - E} - \alpha\left[t_i\left(x_i - \bar{e}_i\right) - t_j\left(x_j - \bar{e}_j\right)\right]$$

and

$$\pi_i^{2,R} = x_i - \frac{x_i(x_i + x_j)}{\theta(1+g) - E} - \beta\frac{T}{2}(x_i + x_j - \hat{e})$$

which are analogous to first-period profits. However, we denote the penalties from the AO in this period as t_i and t_j (as opposed to f_i and f_j in the first period) and the fine of the R as T (as opposed to F in the first period).

The expression of $\pi_i^{2,AO}$ ($\pi_i^{2,R}$) assumes that the AO (R) uses the same quota, $\bar{e}_i$ ($\hat{e}$, respectively), set in the first period. This occurs when the policy is "inflexible." Otherwise, quotas can be revised at the beginning of the second period ("flexible" policy) and are denoted as $\bar{e}_i^1$ and $\bar{e}_i^2$ for the AO, and $\hat{e}^1$ and $\hat{e}^2$ for the R. (Next sections analyze both flexible and inflexible policy regimes.) The profit from facing both regulatory agencies, $\pi_i^{2,B}$, is

$$\pi_i^{2,B} = \pi_i^{2,AO} - \beta\frac{T}{2}(x_i + x_j - \hat{e}).$$

To study the role of the AO and the R on fishermen's appropriation, we examine four cases in which fishermen interact: (i) not facing any form of regulation, (ii) only with the AO, (iii) only with the R, and (iv) with both regulatory agencies (AO and R).

[7] This approach is equivalent to considering the second-period stock to be $\theta - (1-g)E$. As in our approach, when the first-period stock does not regenerate, $g = 0$, the available resource collapses to $\theta - E$; while when it fully regenerates, $g = \frac{E}{\theta}$, the available resource is θ, as in the first period. Ryan et al. (2014) consider that different types of externalities can affect the biological stock of fish at the beginning of the second period. While we do not explicitly model different externalities, parameter g can capture these effects.

3 Equilibrium Analysis without Regulation

As a benchmark, we analyze a setting where fishermen operate without facing the AO or the R. The time structure of the game is the following:

1. In the first stage, every fisherman i simultaneously and independently chooses his first-period appropriation, e_i.
2. In the second stage, every fisherman i observes first-period appropriation decisions, and responds independently selecting his second-period appropriation, x_i.

Solving by backward induction, in the second period every fisherman i solves

$$\max_{x_i \geq 0} \quad \pi_i^{2,NR} = x_i - \frac{x_i(x_i + x_j)}{\theta(1+g) - E}$$

where the fisherman does not face any type of regulation (superscript NR). All proofs are relegated to the appendix.

Lemma 1. *Under no regulation, every fisherman i's second-period equilibrium appropriation is*

$$x_i^{NR}(E) = \frac{[\theta(1+g) - E]}{3}$$

which is positive if and only if $E < \theta(1+g)$.

As expected, second-period appropriation increases in the available stock at the beginning of the second period, $\theta(1+g) - E$. In the first period, fisherman i anticipates $x_i^{NR}(E)$ and $x_j^{NR}(E)$ from Lemma 1, and solves

$$\max_{e_i \geq 0} \ \pi_i^{1,NR} + \delta \pi_i^{2,NR}(x_i^{NR}(E), x_j^{NR}(E))$$

where $\pi_i^{1,NR}$ denotes first-period profits without regulation, and $\delta \in (0,1]$ is the discount factor which, for simplicity, coincides across all players.

Proposition 1. *Under no regulation, every fisherman i's first- and second-period equilibrium appropriation are*

$$e_i^{NR} = \frac{\theta(9-\delta)}{27} \quad \text{and} \quad x_i^{NR} = \frac{\theta(8\delta + 27g + 9)}{81}$$

which are both positive under all parameter values.

Both appropriations are increasing in the abundance of the stock, θ. In addition, first-period (second-period) appropriation is decreasing (increasing) in the discount factor, δ, meaning that as fishermen assign a larger weight to future payoffs, they shift exploitation toward the second period.[8]

[8] The initial condition on g, $g < \frac{E}{\theta}$, holds in this setting if $g < \frac{4(9-2\delta)}{27}$.

4 Flexible policy

We first examine how our previous results are affected by "flexible" policies, meaning that the regulatory agency (AO, R, or B) sets quotas and fines in the first period, before fishermen respond with their first-period appropriation, and has the ability to revise them at the beginning of the second period. This ability is, however, less prevalent in real-life policies, so the next section considers an "inflexible" policy, set at the beginning of the first period and which stays in place in the second period. Hence, the time structure of the game under a flexible policy regime is:

1. In the first period:

   (a) If only the AO is present, it independently chooses a first-period extraction quota for each fisherman, $\overline{e}_i$ and $\overline{e}_j$, and first-period fines, f_i and f_j.

   (b) If only the R is present, it independently chooses a first-period aggregate extraction quota, $\widehat{e}^1$, and a first-period fine, F.

   (c) If both AO and R are present, the R chooses a first-period aggregate extraction quota, $\widehat{e}^1$, and a first-period fine, F. Observing this quota and fine, the AO responds selecting its first-period extraction quota for each fisherman, $\overline{e}_i$ and $\overline{e}_j$, and first-period fines, f_i and f_j.[9]

   (d) Under a given regulatory setting $k = \{AO, R, B\}$, every fisherman i observes the first-period quotas and fines, and responds simultaneously and independently choosing his first-period appropriation, e_i.

2. In the second period, every player observes first-period behavior, and responds as follows:

   (a) If only the AO is present, it independently chooses a second-period extraction quota for each fisherman, $\overline{x}_i$ and $\overline{x}_j$, and second-period fines, t_i and t_j.

   (b) If only the R is present, it independently chooses a second-period aggregate extraction quota, $\widehat{e}^2$, and a second-period fine, T.

   (c) If both AO and R are present, the R chooses a second-period aggregate extraction quota, $\widehat{e}^2$, and a second-period fine, T. Observing this quota and fine, the AO responds selecting its second-period extraction quota for each fisherman, $\overline{x}_i$ and $\overline{x}_j$, and second-period fines, t_i and t_j.

   (d) Under a given regulatory setting $k = \{AO, R, B\}$, every fisherman i observes the second-period quotas and fines, and responds simultaneously and independently choosing his second-period appropriation, x_i.

[9] For completeness, we also considered the setting in which the AO is the first mover and the R is the second mover, showing that our results are qualitatively unaffected, and can be provided by the authors upon request.

Using the above approach, it is easy to show that, under a flexible policy, we obtain the same first- and second-period equilibrium appropriation levels when only an AO is present, when only the R is present, or when both are active. This is mainly explained by both agencies having the same objective, that is, the AO and the R maximize the sum of discounted joint profits, that is,

$$\left(\pi_i^{1,k} + \delta\pi_i^{2,k}\right) + \left(\pi_j^{1,k} + \delta\pi_j^{2,k}\right)$$

which is evaluated at regulatory setting $k = \{AO, R, B\}$. For simplicity, we focus on settings where fishermen appropriate at or above their quotas, rather than strictly below the quotas.

Proposition 2. *Under a flexible policy, first- and second-period equilibrium appropriation levels are*

$$e_i^k = \frac{\theta(4-\delta)}{16} \quad \text{and} \quad x_i^k = \frac{\theta(\delta + 8g + 4)}{32}$$

under every regulatory setting $k = \{AO, R, B\}$*, which satisfies* $e_i^k > x_i^k$ *in every* k*. However, first- and second-period fines are:*

a) $f_i^{AO} = \frac{4+\delta}{16\alpha}$ *and* $t_i^{AO} = \frac{1}{4\alpha}$ *under* AO*;*

b) $F^R = \frac{4+\delta}{8\beta}$ *and* $T^R = \frac{1}{2\beta}$ *under* R*; and*

c) $f_i^B = \frac{4+\delta}{16\alpha}$, $t_i^B = \frac{1}{4\alpha}$, *and* $F^B = T^B = 0$ *under* B*.*

Socially optimal appropriation is lower than under no policy in the first period, $e_i^k < e_i^{NR}$, but it is higher in the second period, $x_i^k > x_i^{NR}(E^{NR})$, which holds for all admissible parameter values. Along with $e_i^k > x_i^k$, we obtain a complete ranking of exploitation levels with and without regulation,

$$x_i^{NR}(E^{NR}) < x_i^k < e_i^k < e_i^{NR}$$

as illustrated in Figure 1. These appropriation levels can be achieved *regardless* of the regulatory setting that fishermen face (under AO, R, or B), entailing no inefficiencies. Intuitively, the internalization of the first-period externality allows fishermen to exploit the resource more intensively in the second period.

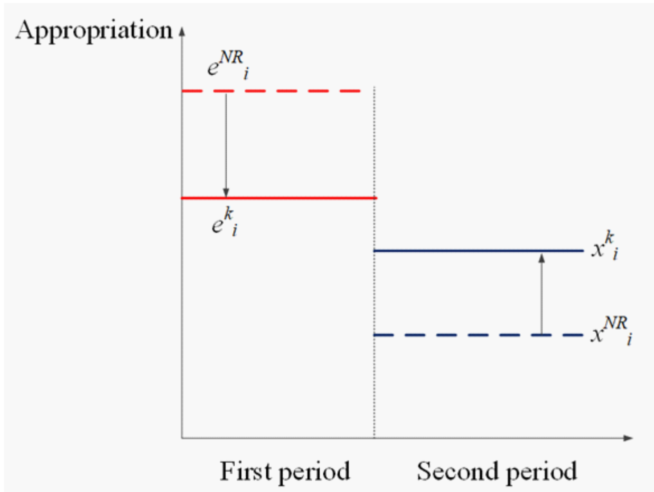

Figure 1. First- and second-period appropriation under a flexible policy regime.

In addition, first-period appropriation is increasing in the initial stock, θ, but decreasing in the fisherman's discount factor, δ, indicating that second-period appropriation (and profits) become more important. Second-period appropriation is, in contrast, increasing in the discount factor, δ, in the initial stock, θ, and the regeneration rate, g. We also observe that fines under AO coincide with those under B. Intuitively, when both regulatory agencies are active, the R sets zero fines in both periods because he can anticipate that the AO's fine will be enough to induce socially optimal appropriation levels.[10]

5 Inflexible policy

We next discuss how our results are affected when fishermen are subject to "inflexible" policies, meaning that the regulatory agency (AO, R, or B) uses the same quota and fines in both periods. Hence, the time structure of the game presented in Section 4 simplifies, since first-period regulation stays in place during the second period and every fisherman i responds choosing their appropriation level, x_i.

Lemma 2. *When only the AO is present under an inflexible policy, first- and second-period equilibrium appropriation levels are*

$$e_i^{AO} = \frac{\theta(18+\delta-3A)}{4\delta} \quad \textit{and} \quad x_i^{AO} = \frac{\theta\,(6+\delta-A)\,[\delta(1+2g)-18+3A]}{8\delta^2}$$

[10] A similar result holds if R acts after the AO, where the AO would anticipate that the fines of the R can induce socially optimal appropriation levels, leading to zero fines from the AO.

and the fine is $f_i^{AO} = \frac{(\delta-18)+3A}{4\alpha\delta}$, *where* $A \equiv \left(36+\delta^2\right)^{1/2}$.

When the AO must set the same quota and fine across both periods, it chooses a linear combination of those under Proposition 2, yielding inefficiencies in both periods (as we confirm in the next section). In other words, the inflexible policy hinders the AO's ability to internalize cost externalities across fishermen. In addition, second-period appropriation increases in the stock abundance, θ, and its growth rate, g, for all parameter values.

Lemma 3. *When only the R is present under an inflexible policy, first- and second-period equilibrium appropriation levels are*

$$\begin{aligned} e_i^R &= \frac{\theta\left[3(6-C)+\delta\left(37-5\delta+C\right)\right]}{196\delta} \quad \textit{and} \\ x_i^R &= \frac{\theta(C-5\delta-6)[\delta(C-5\delta-98g-61)-3(C-6)]}{2744\delta^2} \end{aligned}$$

and the fine is $F^R = \frac{(13\delta-18)+3C}{14\delta\beta}$, *where* $C \equiv \left[36+\delta(25\delta-24)\right]^{1/2}$.

Similar to Lemma 2, socially optimal appropriation in both periods increases in the abundance of the stock, θ, but the fine decreases in the probability to be monitored, β.

Lemma 4. *When both AO and R are present under an inflexible policy, first- and second-period equilibrium appropriation levels are*

$$\begin{aligned} e_i^B &= \frac{\theta\left[1+\delta(1+6\delta)-D(1+2\delta)\right]}{8\delta} \quad \textit{and} \\ x_i^B &= \frac{\theta\left(1+3\delta-D\right)\left[\delta(3+4g-6\delta+2D)-D-1\right]}{16\delta^2} \end{aligned}$$

and fines are $f_i^B = \frac{2-7\delta+3D}{4\alpha\delta}$ *and* $F^B \in \left[0, \frac{2\delta-5}{2\beta\delta}\right]$, *where* $D \equiv (3\delta-1)$.

Therefore, if the fine assigned by the regulator is zero, $F^B = 0$, first-period equilibrium appropriation under B coincides with that under AO, $e_i^B = e_i^{AO}$, and so does that in the second period, $x_i^B = x_i^{AO}$. This result is analogous to that under flexible policy, since the R anticipates the quotas and fines set by the AO, which induces socially optimal appropriation levels, and making the role of the R unnecessary.

6 Regulatory inefficiencies

In this section, we measure the difference in first- and second-period appropriation across policy regimes, $e_i^{k,F} - e_i^{k,IN}$ and $x_i^{k,F} - x_i^{k,IN}$ respectively, where IN and F denote inflexible and flexible regulations. Since no inefficiencies arise in the flexible policy regime (socially optimal appropriation levels emerge in both periods), the difference in appropriation across regimes helps us evaluate the inefficiencies of an inflexible policy. This approach is equivalent to that in the contract theory literature, which measures output inefficiencies between different information settings. For simplicity, this section assumes no discounting.

Corollary 1. *First-period (second-period) equilibrium appropriation under inflexible regulation satisfies* $e_i^{k,IN} > e_i^{k,F}$ *(*$x_i^{k,IN} < x_i^{k,F}$*) for all parameter values, and for every* $k = \{AO, R, B\}$.

Therefore, under inflexible policies, fines are less stringent in the first period, which leads to a more intense first-period appropriation than under flexible policies, yielding a lower second-period appropriation; a ranking that holds under all regulatory settings and all parameter values. Figure 2 superimposes first- and second-period appropriation levels under an inflexible regime in figure 1, where the shaded areas illustrate the inefficiency of the inflexible policy regime ($e_i^{k,IN} - e_i^{k,F}$ in the first period and $x_i^{k,F} - x_i^{k,IN}$ in the second period). When both regulators are present, corollary 1 shows that $e_i^{B,IN} > e_i^{B,F}$ and $x_i^{B,IN} < x_i^{B,F}$ holds, thus giving rise to inefficiencies in either period. In other words, the presence of one or both agencies does not help correct the inefficiencies.

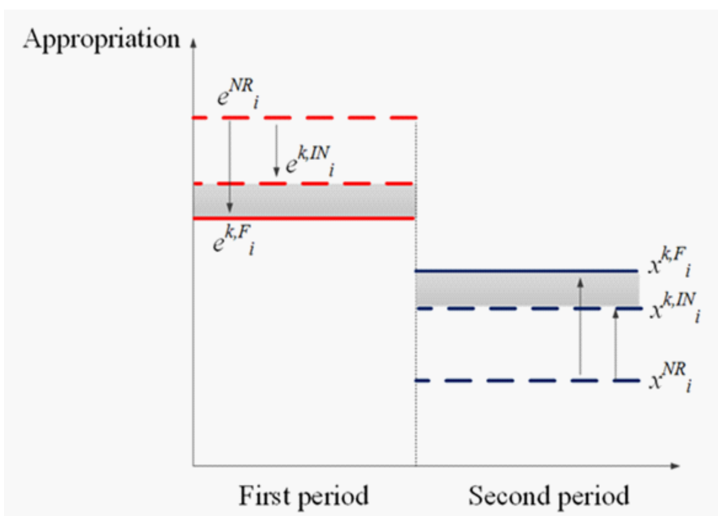

Figure 2. First- and second-period appropriation under an inflexible policy regime.

While our above results identify the presence of inefficiencies in each period, they do not measure their size. Let us evaluate them by considering

$$FPI^k = e_i^{k,IN} - e_i^{k,F} \quad \text{and} \quad SPI^k = x_i^{k,F} - x_i^{k,IN}$$

which denote first- and second-period inefficiencies, respectively. Graphically, the grey shaded area on the left part of figure 2 illustrates FPI^k, while that in the right part of the figure indicates SPI^k. The following corollary ranks these inefficiencies across regulatory settings.

Corollary 2. *First-period inefficiencies satisfy* $FPI^R > FPI^{AO} = FPI^B > 0$ *and, similarly, second-period inefficiencies satisfy* $SPI^R > SPI^{AO} = SPI^B > 0$*, which holds for all parameter values.*

Intuitively, the R generates the largest inefficiency in both periods, which originates from the fact that R has fewer policy tools (aggregate quota and fine) than the AO does (firm-specific quotas and fines). Given this socially insufficient reduction in first-period appropriation by the R, it is understandable that he responds by increasing second-period appropriation less significantly than the AO does, giving rise to the largest second-period inefficiencies as well. The AO and B generate the same (positive) inefficiency, thanks to the AO's larger set of policy tools.

7 Extension - Different objective functions

In previous sections, we consider that AO and R seek to maximize the sum of both firms' discounted profits, net of fines, that is,

$$\left(\pi_i^1 + \delta\pi_i^2\right) + \left(\pi_j^1 + \delta\pi_j^2\right).$$

While this is a natural objective function for the AO, the R may be interested in the biodiversity loss due to aggregate appropriation. In these settings, the R's objective function would be

$$\left(\pi_i^1 + \delta\pi_i^2\right) + \left(\pi_j^1 + \delta\pi_j^2\right) - d\left(E + \delta X\right)$$

where $E \equiv e_i + e_j$ denotes aggregate first-period appropriation, and $X \equiv x_i + x_j$ represents aggregate second-period appropriation. Parameter $d \in [0, 1]$ captures the importance that the R assigns to biodiversity loss or, alternatively, the degree of preference divergence between the AO and the R when setting quotas and fines. When $d = 0$, both regulatory agencies have similar objectives, yielding the same results as in previous sections; when $d > 0$ the R prefers lower appropriation levels than the AO; and when $d = 1$, the R assigns the same importance to aggregate profits and to environmental damage. For simplicity, this section allows agents to discount future payoffs, but assumes that such discounting is extreme, i.e., $\delta > 0$.

7.1 Equilibrium analysis

When no regulatory agency is present, our equilibrium results in Proposition 1 still apply. A similar argument applies when only the AO is present, both under a flexible and inflexible regime. However, when only the R is present, equilibrium results under a flexible policy (Proposition 2b) are affected as follows. (For compactness, we relegate appropriation levels to the proof, focusing here in their comparative statics.)

Lemma 5. *Under a flexible policy, when the* R *is present (with or without* AO*), first- and second-period equilibrium appropriation levels are decreasing in* d*, while the fine is increasing in* d*, for all parameter values.*

When $d = 0$, equilibrium appropriation levels $\tilde{e}_i^{R,F}$ and $\tilde{x}_i^{R,F}$ ($\tilde{e}_i^{B,F}$ and $\tilde{x}_i^{B,F}$) coincide with those in Proposition 2b when only R is present (when both R and AO are present, respectively). When d increases, however, fines become more stringent, leading to lower appropriation levels. Intuitively, the R seeks more conservation as the environmental damage from appropriation increases, which holds when the AO is also present.

Similar results apply under the inflexible policy regime, as the next lemma summarizes.

Lemma 6. *Under an inflexible policy, when only the R is present, first- and second-period equilibrium appropriation levels decrease in d, while the fine increases in d, under all parameter values. However, when both R and AO are present, first-period (second-period) equilibrium appropriation decreases (increases) in d.*

When only R is present, our results are consistent with those in Lemma 3, $\tilde{e}_i^{R,IN}$ and $\tilde{x}_i^{R,IN}$, where $d = 0$, but appropriation levels decrease in both periods as the environmental damage becomes more severe. However, when both agencies are present, first-period appropriation decreases in environmental damage, but second-period appropriation increases, intensifying exploitation and damages. Instead, leaving an environmentally concerned R alone, when an inflexible policy is in place, can help prevent the overexploitation of the CPR.

7.2 Measuring regulatory inefficiencies

In section 6, where $d = 0$, regulatory inefficiencies were measured as follows

$$FPI^k = e_i^{k,IN} - e_i^{k,F} \quad \text{and} \quad SPI^k = x_i^{k,F} - x_i^{k,IN}$$

because the flexible policy regime produced first-best outcomes in all regulatory settings (for all k).[11] When the R considers environmental damages ($d > 0$), however, inefficiencies must be measured by the difference in the appropriation level under an inflexible policy regime relative to the first-best outcome, which in this context is the appropriation level that the R would choose under a flexible regime (as the AO ignores environmental damages), that is,

$$\widetilde{FPI}^k = \tilde{e}_i^{k,IN} - \tilde{e}_i^{R,F} \quad \text{and} \quad \widetilde{SPI}^k = \tilde{x}_i^{R,F} - \tilde{x}_i^{k,IN}$$

which can, alternatively, be expressed as follows

$$\widetilde{FPI}^k = \underbrace{\left(\tilde{e}_i^{k,IN} - \tilde{e}_i^{k,F}\right)}_{\text{Ineffic. from inflexibility}} + \underbrace{\left(\tilde{e}_i^{k,F} - \tilde{e}_i^{R,F}\right)}_{\text{Ineffic. from ignoring externality}}$$

[11] Intuitively, we evaluated how appropriation under the inflexible policy regime in a given regulatory setting k compared against the first-best appropriation level, which was achieved in the flexible regime.

and a similar expression applies to SPI^k, that is,

$$\widetilde{SPI}^k = \left(\tilde{x}_i^{k,F} - \tilde{x}_i^{k,IN}\right) + \left(\tilde{x}_i^{R,F} - \tilde{x}_i^{k,F}\right).$$

Intuitively, $\widetilde{FPI}^k$ embodies two inefficiencies: one arising when regulatory agency k cannot change its quotas and fines across periods in an inflexible regime, as captured by the first term, $\tilde{e}_i^{k,IN} - \tilde{e}_i^{k,F}$; and another stemming from this agency not internalizing the environmental damage in its policies, represented in the second term, $\tilde{e}_i^{k,F} - \tilde{e}_i^{R,F}$. A similar argument applies to $\widetilde{SPI}^k$. The first form of inefficiency was already present in contexts where the R and AO have the same objective function ($d = 0$), but the second form of inefficiency only emerges when these agencies exhibit different objectives ($d > 0$).

As expected, the second form of inefficiency is nil for R and B, since the R considers the externality, but positive for AO, who ignores the externality. The following corollary confirms this result and evaluates the inefficiencies arising in each period. We consider no discounting to facilitate our comparisons.

Corollary 3. *First-period equilibrium appropriation satisfies* $\tilde{e}_i^{k,IN} > \tilde{e}_i^{k,F}$ *under all parameter values, and for every regulatory setting* $k = \{R, AO, B\}$. *Second-period equilibrium appropriation satisfies* $\tilde{x}_i^{k,F} > \tilde{x}_i^{k,IN}$ *for* $k = \{R, AO\}$ *under all parameter values, but* $\tilde{x}_i^{B,IN} > \tilde{x}_i^{B,F}$ *for all* $d > \sqrt{37} - 6 \simeq 0.08$. *In addition, the second source of inefficiency is nil for* R *and* B *in both the first and second period since* $\tilde{e}_i^{R,F} = \tilde{e}_i^{B,F}$ *and* $\tilde{x}_i^{R,F} = \tilde{x}_i^{B,F}$*, whereas for the* AO *it is positive because* $\tilde{e}_i^{AO,F} > \tilde{e}_i^{R,F}$ *and* $\tilde{x}_i^{AO,F} > \tilde{x}_i^{B,F}$.

Therefore, every agency k produces first-period inefficiencies when operating under an inflexible regime, i.e., $\tilde{e}_i^{k,IN} > \tilde{e}_i^{k,F}$ for all k, thus overexploiting the resource relative to its first-best level (first source of inefficiency described above). This result goes in line with that in section 6 (where $d = 0$), but inefficiencies are now augmented because $d > 0$ gives rise to the second source of inefficiency for the AO. This second source of inefficiency is nil for the R and B, since R is present in both settings and it internalizes the biodiversity loss.

In the second period, however, the R and AO underexploit the resource, entailing $\tilde{x}_i^{R,F} > \tilde{x}_i^{R,IN}$ and $\tilde{x}_i^{AO,F} > \tilde{x}_i^{AO,IN}$, whereas the B overexploits it relative to the first best level. This inefficiency is, as in the first period, augmented by the second source of inefficiency (when $d > 0$) for the AO, but is not for the R and B.

Overall, the first form of inefficiency (due to the inflexible policy regime) is present in every regulatory agency k. In contrast, the second form of inefficiency (due to not internalizing environmental damage) is nil if the R is present, as it internalizes the externality, with or without the AO; but becomes positive when the AO is the only agent setting quotas and fines, as this agency ignores environmental damages in its objective function.

The following corollary ranks FPIs across regulatory settings, which are denoted at $\widetilde{FPI}^k$ to differentiate them from first-period inefficiencies in our main model (see Corollary 1).

Corollary 4. *First-period inefficiencies satisfy:*

i $\widetilde{FPI}^R > \widetilde{FPI}^{AO} > \widetilde{FPI}^B > 0$ *if* $d < 0.17$;

ii $\widetilde{FPI}^R > \widetilde{FPI}^B > \widetilde{FPI}^{AO} > 0$ *if* $0.17 \leq d < 0.28$;

iii $\widetilde{FPI}^B > \widetilde{FPI}^R > \widetilde{FPI}^{AO} > 0$ *if* $0.28 \leq d < 0.68$*; and*

iv $\widetilde{FPI}^B > \widetilde{FPI}^{AO} > \widetilde{FPI}^R > 0$ *otherwise.*

First, note that the results in Corollary 4(i) embodies our findings in Corollary 2 as a special case where $d = 0$. Figure 3 depicts $\widetilde{FPI}^R$, which is monotonically decreasing in d, as R internalizes the environmental externality; $\widetilde{FPI}^{AO}$, which is unaffected by d since this agency ignores environmental damages; and $\widetilde{FPI}^B$, which is monotonically increasing in d. This increasing pattern occurs because the AO, upon observing a more stringent aggregate quota from the R, responds relaxing individual quotas to its members, giving rise to more inefficiencies.[12]

The figure also illustrates that, when environmental damages are relatively low ($d < 0.17$), B generates the least inefficiencies, and should thus be promoted. When this damage is moderate ($0.17 \leq d < 0.68$, in cases ii-iii), the AO yields the lowest inefficiencies; and otherwise the R is the regulatory agency that more effectively helps to internalize the (severe) environmental externalities.

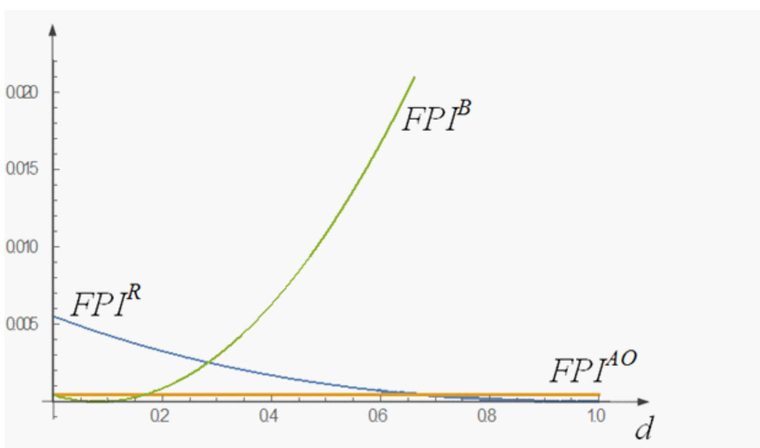

Figure 3. First-period inefficiencies.

We next rank second-period inefficiencies in the three regulatory settings. (Cutoff $\widehat{d}$ is defined, for compactness, in the proof of Corollary 5 in the appendix.)

Corollary 5. *Second-period inefficiencies satisfy:*

i $\widetilde{SPI}^R > \widetilde{SPI}^{AO} \geq \widetilde{SPI}^B > 0$ *if* $d < \sqrt{37} - 6 \simeq 0.08$,

[12] For illustration purposes, the figure normalizes θ to $\theta = 1$, but different values of θ can be provided upon request.

ii $\widetilde{SPI}^{R} > \widetilde{SPI}^{AO} > 0 > \widetilde{SPI}^{B}$ *if* $0.08 \leq d < \widehat{d}$,

iii $\widetilde{SPI}^{AO} > \widetilde{SPI}^{R} > 0 > \widetilde{SPI}^{B}$ *otherwise.*

Corollary 5(i) embodies $d = 0$ as a special case, where $\widetilde{SPI}^{R} > \widetilde{SPI}^{AO} = \widetilde{SPI}^{B}$, as shown in Corollary 2. When d is relatively low, $0 < d < 0.08$, a similar ranking emerges, but B yields smaller inefficiencies than AO because R (who is present in B) helps attenuate the environmental externality. When environmental damages are moderate, $0.08 \leq d < \widehat{d}$, the same ranking still applies but $\widetilde{SPI}^{B} < 0$, as shown in Corollary 3, i.e., $\tilde{x}_i^{R,F} < \tilde{x}_i^{B,IN}$, implying that B overexploits the commons relative to its efficient level. Therefore, choosing the regulatory agency in this setting (R, AO, or B) depends on whether society seeks to avoid an underexploitation of the resource (the smallest one arising with AO) or its overexploitation with B. Finally, when environmental damages become more severe, $d \geq \widehat{d}$, society must compare the (smallest) underexploitation, which happens with R, or the overexploitation that occurs with B.

This result goes in line with that in Corollary 4, as the AO becomes more inefficient, relative to the R and B, when agents' preferences become more misaligned (higher d). In other words, the R generates the most inefficiencies when d is relatively low, $d < \widehat{d}$, and it should not manage the resource. Otherwise the AO is the agent giving rise to the most inefficiencies. In terms of policy implications, the AO (B) should manage the CPR if society prefers inefficiencies originating from the underexploitation (overexploitation) of the resource and damages are relatively low, $d < \widehat{d}$; but R (B) should manage the CPR if society values underexploitation (overexploitation) and damages are relatively severe.

In addition, while cutoff $\widehat{d}$ is highly nonlinear, one can numerically show that it increases in the growth rate of the resource, g. When $g = 0.1$, for instance, this cutoff becomes $\widehat{d} = 0.809$; and when g increases to $g = 0.3$, this cutoff increases to $\widehat{d} = 0.869$. Therefore, the ranking of inefficiencies in Corollary 5(ii) expands when the resource regenerates faster (higher g). Although the specific regulatory agency in cases (ii) and (iii) depends on the trade-off between under- and overexploitation described above, the R is unambiguously welfare reducing and should be avoided, opting for AO or B instead.

For illustration purposes, Table I evaluates first- and second-period inefficiencies in each regulatory setting. First-period inefficiencies exhibit the same patterns as in figure 3. In addition, a faster regeneration rate, g, does not affect first-period inefficiencies, but increases the absolute value of second-period inefficiencies. When environmental damages increase, $\widetilde{SPI}^{B}$ becomes more substantial, indicating a significant overexploitation with B.

		First-period inefficiencies			Second-period inefficiencies		
		$\widetilde{FPI}^R$	$\widetilde{FPI}^{AO}$	$\widetilde{FPI}^B$	$\widetilde{SPI}^R$	$\widetilde{SPI}^{AO}$	$\widetilde{SPI}^B$
$d = 0$	$g = 0$	0.55	0.04	0.04	4.84	1.31	1.31
	$g = 0.1$	0.55	0.04	0.04	5.58	1.52	1.52
	$g = 0.3$	0.55	0.04	0.04	7.07	1.93	1.93
$d = 0.25$	$g = 0$	0.28	0.04	0.17	4.78	1.31	−2.83
	$g = 0.1$	0.28	0.04	0.17	5.31	1.52	−3.24
	$g = 0.3$	0.28	0.04	0.17	6.37	1.93	−4.08
$d = 0.5$	$g = 0$	0.11	0.04	1.08	4.16	1.31	−7.65
	$g = 0.1$	0.11	0.04	1.08	4.50	1.52	−8.69
	$g = 0.3$	0.11	0.04	1.08	5.17	1.93	−10.77
$d = 0.75$	$g = 0$	0.01	0.04	2.78	2.67	1.31	−13.45
	$g = 0.1$	0.01	0.04	2.78	2.83	1.52	−15.12
	$g = 0.3$	0.01	0.04	2.78	3.16	1.93	−18.45
$d = 1$	$g = 0$	0	0.04	5.25	0	1.31	−20.52
	$g = 0.1$	0	0.04	5.25	0	1.52	−22.81
	$g = 0.3$	0	0.04	5.25	0	1.93	−27.39

Table I. First- and second-period inefficiencies.

8 Discussion

Flexible policy yields no inefficiencies. Our paper shows that, when fishermen face a flexible regulatory setting, where quotas can be quickly adjusted across periods, socially optimal appropriation levels arise regardless of the specific regulatory setting (AO, R, or B), yielding no inefficiencies (first best). Relative to no regulation, its presence induces fishermen to reduce (increase) their first-period (second-period) appropriation. This is, for instance, the approach in several Territorial Use Rights for Fishing (TURF) programs, such as the Chilean National Benthic Resources program.

Inflexible policy generates inefficiencies. When regulatory settings are inflexible, meaning that quotas and fines cannot be revised in subsequent periods, inefficiencies emerge in both periods, suggesting that regulation only produces a second-best outcome. The AO, for instance, sets quotas that are a linear combination of what this organization would set under flexible regulation, not being able to fully internalize the cost externalities that fishermen impose on each other in every period. A similar result applies under R or B. In terms of policy recommendations, our results suggest that policies should be revisited every period, as expected, but especially when only the R is active, as this agent generates the largest present discounted inefficiencies under most settings when it ignores environmental damages. This is the case in several countries, such as Vietnam, Indonesia, Sri Lanka, where policies are rarely revised. Similarly, our findings entail that R should not manage the resource when it regenerates fast (such as anchovies and Yellowtail flounder), but its regulatory inefficiencies are less substantial when the CPR regenerates slowly (such as mollusks or American plaice).

Fine comparison. Comparing fines under flexible and inflexible policies, we found that they are less stringent in the first period under inflexible policy, which leads to a larger first-period appropriation under all regulatory settings and all parameter values. Second-period fines are, however, more stringent under inflexible policy, which produces a lower second-period appropriation.

Overlapping regulations. When R and AO exhibit the same objectives, a cooperative can efficiently organize the use of the common pool resource, suggesting that the R can, essentially, step back, allowing the AO to become the only regulating agency in the resource, determining quotas and fines among its members. Our above results are, however, affected when the AO and R exhibit different objectives, such as when the R considers the environmental damage due to aggregate appropriation. When this concern for biodiversity loss is nil, $d = 0$, both agencies' preferences are symmetric, yielding the results described above. When $d > 0$, however, their preferences are asymmetric, with the R having a bias towards lower appropriation levels in every period. In this setting, we show that the R sets more stringent quotas than the AO, as the former seeks to correct for additional externalities (environmental damage) than the AO does, leading to higher fines. Interestingly, the AO benefits from a second-mover advantage, responding to a more stringent aggregate quota from the AO by relaxing the individual quotas on its members.

Regulatory inefficiencies, symmetric agencies. We also measure total inefficiencies, finding that they are increasing in the growth rate of the stock, g, in all regulatory settings. In addition, when agents have the same objective function, B is preferable while R generates the largest inefficiencies across periods. Overall, this finding indicates that having the R alone is the less desirable alternative in terms of welfare gains, as the AO alone or B yield a larger welfare under all parameter conditions, particularly the latter. This result entails, as a policy recommendation, that the AO should be an active agent in the regulatory process, setting quotas and fines to its members, both when the R is present and absent.

Regulatory inefficiencies, asymmetric agencies. When R and AO have different objective functions (asymmetric agencies), the above ranking in total inefficiencies changes, as now all agencies generate inefficiencies, stemming from either the inflexibility of the policy or the asymmetry in objectives across agencies. Specifically, when environmental damages are relatively low, the R generates the most inefficiencies, both in the first and second periods, and it should not manage the resource. In this case, the AO (B) should regulate the CPR if society prefers that inefficiencies originate from the underexploitation (overexploitation) of the resource. However, when environmental damages are severe, the AO is generally the agent giving rise to the most inefficiencies, calling for the R (B) to manage the CPR if society prefers underexploitation (overexploitation).

Further research. Our model can be extended along different dimensions. First, the resource could be also exploited by individual fishermen who are not affiliated to an organization. The R and AO would, however, anticipate this additional appropriation, affecting its own decisions, and the R could set fines on this fishermen to reduce overexploitation. Second, one could allow for incomplete information between the R and AO, as the latter is often better informed about the stock's abundance than the former. In that setting, if the R plays before the AO, the R's decision would just be based on its expected stock, without qualitatively affecting our complete information results. However, if the AO plays first, its quotas and fines decisions could be used as a signal by the uninformed player (R) to infer the stock's abundance. Third, the model could be extended to allow for more periods, where the AO receives a license from the R, which can be renewed after the second period, as it is often the case in TURFs, thus providing the R with an additional policy tool (the renewal of the AO's license) which he can use to discipline the AO's extraction. Finally, one could allow for the possibility of imperfect monitoring in flexible or inflexible regulation and how our results are affected.

9 Appendix

9.1 *Proof of Lemma 1*

In the second period, under no regulation, every fisherman i solves

$$\max_{x_i \geq 0} \quad \pi_i^{2,NR} = x_i - \frac{x_i(x_i + x_j)}{\theta(1+g) - E}$$

Differentiating with respect to x_i, yields

$$1 - \frac{2x_i + x_j}{\theta(1+g) - E} = 0$$

Solving for x_i, we find fisherman i's a best response function

$$x_i(x_j) = \begin{cases} \frac{\theta(1+g)-E}{2} - \frac{x_j}{2} \text{ if } x_j < \theta(1+g) - E \\ 0 \quad \text{otherwise.} \end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for x_i and x_j, we obtain second-period equilibrium appropriations

$$x_i^{NR}(E) = \frac{\theta(1+g) - E}{3}$$

which are positive if $E < \theta(1+g)$.

9.2 *Proof of Proposition 1*

In the first period, without regulation, every fisherman i solves

$$\max_{e_i \geq 0} \quad \pi_i^{1,NR} + \delta\pi_i^{2,NR}(x_i^{NR}(E), x_j^{NR}(E))$$

where second-period profits, evaluated at $x_i^{NR}(E) = x_j^{NR}(E) = \frac{\theta(1+g)-E}{3}$, are

$$\pi_i^{2,NR}(x_i^{NR}(E), x_j^{NR}(E)) = \frac{\theta(1+g) - E}{9}.$$

Therefore, every fisherman i solves

$$\max_{e_i \geq 0} \quad e_i - \frac{e_i(e_i + e_j)}{\theta} + \delta \left[\frac{\theta(1+g) - (e_i + e_j)}{9} \right]$$

since $E = e_i + e_j$. Differentiating with respect to e_i, yields

$$1 - \frac{\delta}{9} - \frac{2e_i + e_j}{\theta} = 0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$e_i^{NR} = \frac{\theta(9-\delta)}{27}.$$

which is positive since $\delta < 1$ by assumption. Therefore, second-period equilibrium appropriation is

$$x_i^{NR} = \frac{\left[\theta(1+g) - (e_i^{NR} + e_j^{NR})\right]}{3} = \frac{\theta(8\delta + 27g + 9)}{81},$$

which is positive for all parameter values.

9.3 *Proof or Proposition 2*

9.3.1 Only AO is present

Fourth stage. In the fourth stage, every fisherman i solves

$$\max_{x_i \geq 0} \quad \pi_i^{2,AO} = x_i - \frac{x_i\,(x_i + x_j)}{[\theta(1+g) - E]} - \alpha\,[t_i\,(x_i - \bar{x}_i) - t_j\,(x_j - \bar{x}_j)]$$

Differentiating with respect to x_i, yields

$$\frac{2x_i + x_j - \alpha t_i\,[\theta(1+g) - E] + E - (1+g)\theta}{\theta(1+g) - E} = 0$$

Solving for x_i, we obtain fisherman i's best response function

$$x_i(x_j) = \begin{cases} \frac{1}{2}\left[(1-\alpha t_i)\,(\theta(1+g) - E)\right] - \frac{1}{2}x_j \text{ if } x_j < (1-\alpha t_i)\,(\theta(1+g) - E) \\ 0 \quad \text{otherwise.} \end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for x_i and x_j in the above best response functions, we obtain second-period equilibrium appropriation

$$x_i^{AO}(E) = \frac{[1 - \alpha\,(2t_i - t_j)]\,[\theta(1+g) - E]}{3}$$

which exceeds that in Lemma 1, $x_i^{NR}(E)$, if and only if $t_i < \frac{t_j}{2}$. In the special case that both fishermen receive the same penalty, $t_i = t_j$, second-period equilibrium appropriation coincides, i.e., $x_i^{NR}(E) = x_i^{AO}(E)$, since fines do not provide fisherman i with a cost advantage, if $t_i < \frac{t_j}{2}$, or a cost disadvantage, if $t_i > \frac{t_j}{2}$.

Third stage. The *AO* chooses quotas and fines that maximize joint profits for the second period.

$$
\begin{aligned}
\max_{\bar{x}_i,\bar{x}_j,f_i,f_j\geq 0} \quad \pi_o \quad &= \quad \left[x_i - \frac{x_i\,(x_i+x_j)}{[\theta(1+g)-E]} - \alpha\left[t_i\,(x_i-\bar{x}_i) - t_j\,(x_j-\bar{x}_j)\right]\right] \\
&\quad + \left[x_j - \frac{x_j\,(x_i+x_j)}{[\theta(1+g)-E]} - \alpha\left[t_j\,(x_j-\bar{x}_j) - t_i\,(x_i-\bar{x}_i)\right]\right].
\end{aligned}
$$

We first identify the socially optimal appropriation levels, that is, the values of x_i and x_j that maximize second-period joint profits, as follows,

$$
\max_{x_i,x_j\geq 0} \quad \pi_o = \left[x_i - \frac{x_i\,(x_i+x_j)}{[\theta(1+g)-E]}\right] + \left[x_j - \frac{x_j\,(x_i+x_j)}{[\theta(1+g)-E]}\right].
$$

Differentiating with respect to x_i, yields

$$
\frac{\theta(1+g)-E-x_i-x_j}{\theta(1+g)-E} = 0
$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$
x_i^{SO} = \frac{\theta(1+g)-E}{4}.
$$

Setting it equal to the equilibrium first-period appropriation, $x_i^{SO} = x_i^*(E)$ and $x_j^{SO} = x_j^*(E)$, we obtain

$$
\begin{aligned}
\frac{\theta(1+g)-E}{4} \quad &= \quad \left[1-\alpha\,(2t_i-t_j)\right]\left[\theta(1+g)-E\right]/3 \\
\frac{\theta(1+g)-E}{4} \quad &= \quad \left[1-\alpha\,(2t_j-t_i)\right]\left[\theta(1+g)-E\right]/3
\end{aligned}
$$

which, solving for t_i and t_j , yields the fine that induces fishermen i and j to appropriate exactly x_i^{SO} and x_j^{SO}, that is,

$$
t_i^{SO} = t_j^{SO} = \frac{1}{4\alpha}
$$

which is positive for all α values.

Second stage. In the second stage, every fisherman i anticipates equilibrium second-period appropriations, $x_i^{AO}(E)$ and $x_j^{AO}(E)$, and solves

$$
\max_{e_i\geq 0} \quad \pi_i^{1,AO} + \delta\pi_i^{2,AO}\left(x_i^{AO}(E), x_j^{AO}(E)\right)
$$

Differentiating with respect to e_i, yields

$$
\frac{\theta\,(8-\delta-8\alpha f_i) - 8(2e_i+e_j)}{8\theta} = 0
$$

Solving for e_i, we obtain a best response function

$$e_i(e_j) = \begin{cases} \frac{1}{16}\theta(8-\delta-8\alpha f_i) - \frac{1}{2}e_j, \text{ if } e_j < \frac{1}{8}\theta(8-\delta-4\alpha f_i), \\ 0 \ \text{ otherwise.} \end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for e_i and e_j in the above best response functions, we obtain first-period equilibrium appropriation.

$$e_i^{AO} = \frac{1}{24}\theta\left[8-\delta-8\alpha(2f_i-f_j)\right]$$

which is positive if and only if $f_i < \frac{f_j}{2}$. Therefore, e_i^{AO} increases in the abundance of the stock, θ, and in fisherman j's penalty, but decreases in fisherman i's penalty.

First stage. The AO chooses quotas and fines that maximize joint profits, as follows.

$$\max_{\bar{e}_i,\bar{e}_j,f_i,f_j\geq 0} \left[ei - \frac{e_i\left(e_i+e_j\right)}{\theta} - \alpha\left(f_i\left(e_i-\bar{e}_i\right) - f_j\left(e_j-\bar{e}_j\right)\right) + \delta\pi_i^{2,AO}\left(x_i^{AO}(E), x_j^{AO}(E)\right)\right]$$
$$+\left[e_j - \frac{e_j\left(e_i+e_j\right)}{\theta} - \alpha\left(f_j\left(e_j-\bar{e}_j\right) - f_i\left(e_i-\bar{e}_i\right)\right) + \delta\pi_j^{2,AO}\left(x_i^{AO}(E), x_j^{AO}(E)\right)\right]$$

Alternatively, this organization first finds the first-period socially optimal appropriation, e_i^{SO} and e_j^{SO}, sets them as quotas, and then identifies the fines f_i and f_j that induce fishermen to appropriate at the socially optimal levels e_i^{SO} and e_j^{SO}, that is, $e_i^{AO} = e_i^{SO}$ for every fisherman i. In particular, socially optimal appropriation solves

$$\begin{aligned} \max_{e_i,e_j\geq 0} \ \pi_o \ &= \ \left[e_i - \frac{e_i(e_i+e_j)}{2\theta} + \delta\pi_i^{2,AO}\left(x_i^{AO}(E), x_j^{AO}(E)\right)\right] \\ &\quad + \left[e_j - \frac{e_j(e_i+e_j)}{2\theta} + \delta\pi_j^{2,AO}\left(x_i^{AO}(E), x_j^{AO}(E)\right)\right] \end{aligned}$$

Differentiating with respect to e_i, yields

$$\frac{\theta(4-\delta) - 8(e_i+e_j)}{4\theta} = 0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$e_i^{SO} = \frac{\theta(4-\delta)}{16}.$$

Setting it equal to the equilibrium first-period appropriation, $e_i(f_i, f_j)$, that is,

$$\frac{\theta(4-\delta)}{16} = \frac{1}{24}\theta\left[8-\delta-8\alpha(2f_i-f_j)\right]$$

which, solving for f_i, yields

$$f_i^{AO} = \frac{4+\delta}{16\alpha}.$$

which is positive for all parameter values. Inserting these results into $x_i^{AO}(E)$, yields a second-period equilibrium appropriation $x_i^{AO} = \frac{1}{32}\theta(\delta + 8g + 4)$. As expected, first-period socially optimal appropriation, e_i^{SO}, is lower than in the benchmark case without regulation, e_i^{NR}, for all parameters values.

9.3.2 Only R is present

Fourth stage. In the fourth stage, every fisherman i solves

$$\max_{x_i \geq 0} \quad \pi^{2,R} = x_i - \frac{x_i\,(x_i + x_j)}{\theta(g+1) - E} - \beta\frac{T}{2}\,(x_i + x_j - \hat{x}_i)$$

Differentiating with respect to x_i, yields

$$1 - \frac{2x_i + x_j}{[\theta(1+g) - E]} - \frac{\beta T}{2} = 0$$

Solving for x_i, we obtain fisherman i's best response function

$$x_i(x_j) = \begin{cases} \frac{1}{4}\,(2 - T\beta)\,[\theta(1+g) - E] - \frac{1}{2}x_j & \text{if } x_j < \frac{1}{2}\,(2 - \beta T)\,[\theta(1+g) - E] \\ 0 \quad \text{otherwise.} & \end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for x_i and x_j, we obtain second-period equilibrium appropriation

$$x_i^R(E) = \frac{(2 - \beta T)\,[\theta(1+g) - E]}{6}$$

which exceeds second-period appropriation without regulation, $x_i^{NR}(E)$, if and only if $T < \frac{1}{\beta}$. Therefore, $x_i^R(E)$ increases in the available stock at the begin of the second period, $\theta(1+g) - E$, but decreases in the expected fine, βT.

Third stage. The R chooses the aggregate quota and fines that maximize joint profits for the second period, as follows.

$$\begin{aligned} \max_{\hat{x}, T \geq 0} \quad \pi_o \quad = \quad & \left[x_i - \frac{x_i\,(x_i + x_j)}{[\theta(g+1) - E]} - \beta\frac{T}{2}(x_i + x_j - \hat{x})\right] \\ & + \left[x_j - \frac{x_j\,(x_i + x_j)}{[\theta(g+1) - E]} - \beta\frac{T}{2}(x_i + x_j - \hat{x})\right] + \beta T(x_i + x_j - \hat{x}) \end{aligned}$$

where the last term in every square bracket denotes the equal share of the fine, $\frac{T}{2}$, that every fisherman pays if their aggregate appropriation, $x_i + x_j$, exceeds the aggregate quota, $\hat{x}$. The last term guarantees that the fine is revenue neutral. The above maximization problem can be rewritten as follows,

$$\max_{\hat{x},T\geq 0} \quad \pi_o = x_i + x_j - \frac{(x_i + x_j)^2}{[\theta(g+1) - E]}.$$

We now seek to find the socially optimal second-period appropriation and later on identify the fine that induces fishermen to choose this appropriation level. Differentiating with respect to x_i, and invoking symmetry yields

$$x_i^{SO}(E) = \frac{\theta(1+g) - E}{4}.$$

Setting it equal to the equilibrium second-period appropriation found above, $x_i^R(E)$, we find that $x_i^{SO}(E) = x_i^R(E)$, that is,

$$\frac{(2-\beta T)\,[\theta(1+g) - E]}{6} = \frac{\theta(1+g) - E}{4}$$

and solving for T, we obtain

$$T^R = \frac{1}{2\beta}$$

which is positive for all β values.

Second stage. In the second stage, every fisherman i anticipates equilibrium second-period appropriations, $x_i^R(E)$ and $x_j^R(E)$, and solves

$$\max_{e_i\geq 0} \quad \pi_i^{1,R} + \delta\pi_i^{2,R}\left(x_i^R(E), x_j^R(E)\right)$$

Differentiating with respect to e_i, yields

$$\frac{\theta(8 - 4\beta F - \delta) - 8(e_i + 2e_j)}{8\theta} = 0$$

Then, solving for e_i, we obtain the following best response function

$$e_i(e_j) = \begin{cases} \frac{\theta(8-4\beta F-\delta)}{8} - \frac{1}{2}e_j, & \text{if } e_j < \frac{\theta(8-4\beta F-\delta)}{4}, \\ 0 & \text{otherwise.} \end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for e_i and e_j, we obtain first-period equilibrium appropriation

$$e_i^R = \frac{\theta(8 - 4\beta F - \delta)}{24}$$

which increases in the abundance of the initial stock, θ, but decreases in fisherman i's expected penalty.

First stage. The R chooses the aggregate quotas and fine that maximize joint profits, as follows.

$$\max_{\widehat{e},F\geq 0} \left[\pi_i^{1,R} + \delta\pi_i^{2,R}\left(x_i^R(E), x_j^R(E)\right)\right]$$
$$+\left[\pi_j^{1,R} + \delta\pi_j^{2,R}\left(x_i^R(E), x_j^R(E)\right)\right]$$

We start finding the first-period socially optimal appropriation, and then identify the fine F that induces every fishermen to appropriate at the socially optimal level. To find the first-period socially optimal appropriation levels, the R solves

$$\max_{e_i,e_j\geq 0} \left[e_i - \frac{e_i(e_i+e_j)}{\theta} + \delta\pi_i^{2,R}\left(x_i^R(E), x_j^R(E)\right)\right]$$
$$+\left[e_j - \frac{e_j(e_i+e_j)}{\theta} + \delta\pi_j^{2,R}\left(x_i^R(E), x_j^R(E)\right)\right]$$

Differentiating with respect to e_i and e_j and solving, yields

$$\frac{\theta(4-\delta)+8(e_i+e_j)}{4\theta} = 0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$\widehat{e} = e_i^{SO} = \frac{\theta(4-\delta)}{16}.$$

Setting it equal to the equilibrium first-period appropriation, we obtain $e_i^{SO} = e_i^R$, or

$$\frac{\theta(4-\delta)}{16} = \frac{\theta\left(2-\beta F\right)}{6}$$

which, solving for F, yields a fine

$$F^R = \frac{4+\delta}{8\beta}.$$

which is positive for all parameter values. Inserting this result into $x_i^{SO}(E) = \frac{\theta(1+g)-E}{4}$, we find that second-period equilibrium appropriation is

$$x_i^R = \frac{\theta(\delta+8g+4)}{32}$$

which is also positive for all parameter values. As in the case where only the AO is present, e_i^R, is lower than that in the benchmark case, e_i^{NR}, for all parameters values.

9.3.3 Both R and AO are present

Sixth stage. Fisherman i's maximization problem is

$$\max_{x_i \geq 0} \quad \pi_i^{2,B} = x_i - \frac{x_i(x_i + x_j)}{\theta(1+g) - E} - \alpha\left[t_i(x_i - \bar{x}_i) - t_j(x_j - \bar{x}_j)\right] - \beta\frac{T}{2}(x_i + x_j - \hat{x})$$

Where the first term represents fisherman i's total revenue, the second term is its total extraction cost, the third term denotes the sanction, net from the organization monitoring, and the last term is the penalty if aggregate extractions exceed the quota. Differentiating with respect to x_i, we obtain

$$1 - \frac{\beta T}{2} - \alpha t_i - \frac{2x_i + x_j}{\theta(1+g) - E} = 0.$$

Solving for x_i, we obtain fisherman i's best response function.

$$x_i(x_j) = \begin{cases} \frac{[\theta(1+g)-E][2(1-\alpha t_i)-\beta T]}{4} - \frac{x_j}{2} & \text{if } x_j < \frac{1}{2}\theta(1+g) - E]\left[2(1-\alpha t_i) - \beta T\right] \\ 0 \quad \text{otherwise.} \end{cases}$$

Simultaneously solving for x_i and x_j, we obtain the equilibrium extraction,

$$x_i(t_i, t_j, T) = \frac{\left[\theta(1+g) - E\right]\left[2\alpha(t_j - 2t_i) + 2 - \beta T\right]}{6}$$

which increases in the available stock, $\theta(1+g) - E$, and in his rival's penalty, t_j. However, it decreases in fisherman i's penalty, t_i and the expected fine from the regulator, βT.

Fifth stage. The AO chooses quotas and fines that maximize joint profits for the second period, as follows.

$$\begin{aligned} \max_{\bar{x}_i, \bar{x}_j, t_i, t_j} \quad & \left[x_i - \frac{x_i\left(x_i + x_j\right)}{\left[\theta(1+g) - E\right]} - \alpha\left[t_i(x_i - \bar{x}_i) - t_j(x_j - \bar{x}_j)\right] - \beta\frac{T}{2}(x_i + x_j - \hat{x})\right] \\ & + \left[x_j - \frac{x_j\left(x_i + x_j\right)}{\left[\theta(1+g) - E\right]} - \alpha\left[t_j(x_j - \bar{x}_j) - t_i(x_i - \bar{x}_i)\right] - \beta\frac{T}{2}(x_i + x_j - \hat{x})\right] \end{aligned}$$

Differentiating with respect to x_i, yields

$$\frac{\left[\theta(1+g) - E\right](1 - \beta T) - 2(x_i + x_j)}{\theta(1+g) - E} = 0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$x_i^B = \frac{\left[\theta(1+g) - E\right](1 - \beta T)}{4}.$$

Setting it equal to the equilibrium second-period appropriation found above, $x_i(t_i, t_j, T)$, we obtain a penalty

$$t_i^B = \frac{1+\beta T}{4\alpha}$$

which is positive for all parameter values.

Fourth stage. The R chooses the aggregate quota and fine that maximize joint profits for the second period, as follows.

$$\max_{\hat{x},T\geq 0} \left[x_i - \frac{x_i\,(x_i+x_j)}{\theta(1+g)-E}\right] + \left[x_j - \frac{x_j\,(x_i+x_j)}{\theta(1+g)-E}\right]$$

where we do not include the payment of half of the fine, $T/2$, by each fisherman, since the fine collection is returned to fishermen as a lump sum transfer (for more details, see the case in which only R is present in the previous section of this proof).

We first identify socially optimal appropriation levels and then the quotas and fines that induce fishermen to choose these appropriation levels. Differentiating with respect to x_i in the above expression, yields

$$\frac{\theta(1+g)-E-2(x_i-x_j)}{\theta(1+g)-E} = 0.$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain the first-period socially optimal appropriation level

$$\widehat{x} = x_i^{SO} = \frac{\theta(1+g)-E}{4}.$$

Setting it equal to the equilibrium second-period appropriation found above, x_i^B, we find

$$\frac{[\theta(1+g)-E]\,(1-\beta T)}{4} = \frac{\theta(1+g)-E}{4}$$

or

$$T^B = 0$$

Therefore, the AO penalty in this period becomes $t_i^B = \frac{1}{4\alpha}$.

Third stage. Fisherman i anticipates equilibrium second-period profits, $\pi_i^2(x_i^*, x_j^*)$, and solves the following problem

$$\max_{e_i\geq 0}\ \pi_i^{1,B} = \left[e_i - \frac{e_i(e_i+e_j)}{\theta} - \alpha\left[f_i(e_i-\bar{e}_i) - f_j(e_j-\bar{e}_i)\right] - \beta\frac{F}{2}(e_i+e_j-\hat{e})\right] + \delta\pi_i^{2,B}(x_i^B, x_j^B)$$

where the terms in brackets denote first-period profits and the second-period profits are evaluated at first-period appropriation, $E \equiv e_i + e_j$.

Differentiating with respect to e_i, yields

$$\frac{\theta\left[8(1-\alpha f_i) - 4\beta F - \delta\right] - 8(2e_i+e_j)}{8\theta} = 0$$

Solving for e_i, we obtain fisherman i's best response function

$$e_i(e_j) = \begin{cases} \frac{\theta}{16}\left[8(1-\alpha f_i) - 4\beta F - \delta\right] - \frac{1}{2}e_j, \text{if } e_j < \frac{\theta}{8}\left[8(1-\alpha f_i) - 4\beta F - \delta\right], \\ 0 \ \text{ otherwise.} \end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for e_i and e_j, we obtain first-period equilibrium appropriation.

$$e_i^B = \frac{\theta\left[8(1-\alpha f_i) + 8f_j - 4\beta F - \delta\right]}{24}.$$

Second stage. The AO chooses quotas and fines that maximize joint profits for both periods, as follows.

$$\max_{\bar{e}_i, \bar{e}_j, f_i, f_j \geq 0} \left[\pi_i^{1,AO} + \delta\pi_i^{2,AO}\left(x_i^{AO}(E), x_j^{AO}(E)\right)\right] + \left[\pi_j^{1,AO} + \delta\pi_j^{2,AO}\left(x_i^{AO}(E), x_j^{AO}(E)\right)\right]$$

Similar than before, the above maximization function can be rearranged as follows,

$$\max_{e_i, e_j \geq 0} \left[e_i - \frac{e_i(e_i+e_j)}{2\theta} - \alpha\left[f_i(x_i - \bar{x}_i) - f_j(x_j - \bar{x}_j)\right] - \beta\frac{F}{2}\left(e_i + e_j - \hat{e}\right) + \delta\pi_i^{2,AO}\left(x_i^{AO}(E), x_j^{AO}(E)\right)\right]$$
$$+ \left[e_j - \frac{e_j(e_i+e_j)}{2\theta} - \alpha\left[f_j(x_j - \bar{x}_j) - f_i(x_i - \bar{x}_i)\right] - \beta\frac{F}{2}\left(e_i + e_j - \hat{e}\right) + \delta\pi_j^{2,AO}\left(x_i^{AO}(E), x_j^{AO}(E)\right)\right]$$

Differentiating with respect to e_i, yields

$$\frac{\theta\left[4\left(1 - \beta F\right) - \delta\right] - 8\left(e_i + e_j\right)}{4\theta} = 0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$e_i^B(F) = \frac{\theta\left[4\left(1 - \beta F\right) - \delta\right]}{16}.$$

Setting it equal to the equilibrium first-period appropriation found above, e_i^B, we find

$$\frac{\theta\left[8(1-\alpha f_i) + 8f_j - 4\beta F - \delta\right]}{24} = \frac{\theta\left[4\left(1 - \beta F\right) - \delta\right]}{16}$$

which, solving for f_i, yields

$$f_i^B(F) = \frac{4\left(1 + \beta F\right) + \delta}{16\alpha}$$

which is positive for all parameter values. In addition, equilibrium appropriation e_i^B is lower than that in the benchmark case (no form of regulation).

First period. The R chooses an aggregate quota and fine that maximize joint profits for both periods, as follows.

$$\max_{\widehat{e},F\geq 0} \pi_o = \left[e_i - \frac{e_i(e_i+e_j)}{\theta} + \delta\pi_i^{2,R}\left(x_i^R(E), x_j^R(E)\right)\right] + \left[e_j - \frac{e_j(e_i+e_j)}{\theta} + \delta\pi_j^{2,R}\left(x_i^R(E), x_j^R(E)\right)\right]$$

We first find the first-period appropriation levels that maximize the above objective function (i.e., socially optimal appropriation). In particular, differentiating with respect to e_i, yields

$$\frac{\theta(4-\delta) - 8\left(e_i + e_j\right)}{4\theta} = 0$$

Invoking symmetry, we obtain

$$e_i^B = \frac{\theta(4-\delta)}{16}.$$

Setting it equal to the equilibrium first-period appropriation found above, e_i^B, we obtain

$$\frac{\theta\left[4\left(1-\beta F\right)-\delta\right]}{16} = \frac{\theta(4-\delta)}{16}$$

Solving for F, yields $F^B = 0$, which entails that the fine from the AO in this period is $f_i^B = \frac{4+\delta}{16\alpha}$. Inserting these results into second-period appropriation, $x_i^B(E)$, we find that

$$x_i^B = \frac{\theta(\delta+8g+4)}{32}$$

which is positive for all parameter values.

Comparison. It is easy to show that $e_i^k > x_i^k$ for every regulatory setting k if and only if

$$\frac{\theta(4-\delta)}{16} > \frac{\theta(\delta+8g+4)}{32}$$

which simplifies to $g < \frac{4-3\delta}{8}$. This condition on g, however, is satisfied since the initial condition, $g < \frac{E}{\theta}$, yields $g < \frac{4-\delta}{8}$ in this setting. Therefore, for all admissible values of g, first-period equilibrium appropriation exceeds second-period appropriation $e_i^k > x_i^k$.

9.4 *Proof of Lemma 2*

Third stage. In the third stage, every fisherman i solves

$$\max_{x_i\geq 0} \pi_i^{2,AO} = x_i - \frac{x_i(x_i+x_j)}{[\theta(1+g)-E]} - \alpha\left[f_i\left(x_i-\bar{e}_i\right) - f_j\left(x_j-\bar{e}_j\right)\right]$$

Differentiating with respect to x_i, yields

$$\frac{\theta(1+g)-E](1-\alpha f_i)-(2x_i+x_j)}{\theta(1+g)-E}=0$$

Solving for x_i, we obtain a best response function

$$x_i(x_j)=\begin{cases}\frac{1}{2}\left[\theta(1+g)-E\right](\alpha f_i-1)-\frac{1}{2}x_j \text{ if } x_j<\left[\theta(1+g)-E\right](\alpha f_i-1)\\ 0 \;\; \text{otherwise.}\end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for x_i and x_j, we obtain second-period equilibrium appropriation

$$x_i^{AO}(E)=\frac{\left[\theta(1+g)-E\right]\left[1-\alpha\left(2f_i-f_j\right)\right]}{3}$$

which is positive if $\alpha<\frac{1}{2f_i-f_j}$.

Second stage. In the second stage, every fisherman i anticipates equilibrium second-period appropriations, $x_i^{AO}(E)$ and $x_j^{AO}(E)$, and solves

$$\max_{e_i\geq 0}\;\; \pi_i^{1,AO}+\delta\pi_i^{2,AO}\left(x_i^{AO}(E),x_j^{AO}(E)\right)$$

Differentiating with respect to e_i, yields

$$1-\frac{e_i}{\theta}-\frac{e_i+e_j}{\theta}-\alpha f_i-\frac{1}{9}\delta\left[1+\alpha\left(4f_i-5f_j\right)\left(\alpha\left(f_i+f_j\right)-1\right)\right]=0$$

Solving for e_i, we obtain fisherman i's best response function

$$e_i(e_j)=\begin{cases}\frac{\theta\left[9-\delta+\alpha\left(f_i(4\delta+\alpha\delta f_j-9)-4\alpha\delta f_i^2+5\delta f_j(\alpha f_j-1)\right)\right]}{18}-\frac{1}{2}e_j,\\ \text{if } e_j<\frac{\theta\left[9-\delta+\alpha\left(f_i(4\delta+\alpha\delta f_j-9)-4\alpha\delta f_i^2+5\delta f_j(\alpha f_j-1)\right)\right]}{9},\\ 0 \;\; \text{otherwise.}\end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for e_i and e_j in the above best response functions, we obtain first-period equilibrium appropriation.

$$e_i^*=\frac{\theta\left[\alpha\left[f_i\left(13\delta+\alpha\delta f_j-18\right)-13\alpha\delta f_i^2+f_j\left(9-14\delta+14\alpha\delta f_j\right)\right]+9-\delta\right]}{27}$$

which is positive for all admissible values of α and δ.

First stage. The AO chooses quotas and fines that maximize joint profits, as follows.

$$\max_{\bar{e}_i,\bar{e}_j,f_i,f_j\geq 0} \quad \pi_o = \left[e_i - \frac{e_i(e_i+e_j)}{\theta} - \alpha\left[f_i\left(x_i-\bar{e}_i\right) - f_j\left(x_j-\bar{e}_j\right)\right] + \delta\pi_i^{2,AO}\left(x_i^{AO}(E), x_j^{AO}(E)\right)\right]$$
$$+\left[e_j - \frac{e_j(e_i+e_j)}{\theta} - \alpha\left[f_j\left(x_j-\bar{e}_j\right) - f_i\left(x_i-\bar{e}_i\right)\right] + \delta\pi_j^{2,AO}\left(x_i^{AO}(E), x_j^{AO}(E)\right)\right]$$

which simplifies to

$$\max_{\bar{e}_i,\bar{e}_j,f_i,f_j\geq 0} \quad \pi_o = \left[e_i - \frac{e_i(e_i+e_j)}{\theta} + \delta\pi_i^{2,AO}\left(x_i^{AO}(E), x_j^{AO}(E)\right)\right]$$
$$+\left[e_j - \frac{e_j(e_i+e_j)}{\theta} + \delta\pi_j^{2,AO}\left(x_i^{AO}(E), x_j^{AO}(E)\right)\right]$$

Similar than before, we first find socially optimal appropriation levels, and then the corresponding fines. Differentiating with respect to e_i, yields

$$\frac{\theta\left[9-2\delta+\alpha\delta\left(f_i+f_j\right)\left(\alpha\left(f_i+f_j\right)-1\right)\right]-18(e_i+e_j)}{9\theta}=0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we find

$$e_i^{SO} = \frac{\theta\left[9-2\delta+\delta\alpha\left(f_i+f_j\right)\left(\alpha\left(f_i+f_j\right)-1\right)\right]}{36}.$$

Setting it equal to the equilibrium second-period appropriation, $e_i(f_i, f_j)$, we obtain

$$f_i^{AO} = \frac{(\delta-18)+3A}{4\alpha\delta}$$

where $A = \left(36+\delta^2\right)^{1/2}$ and f_i^{AO} is positive for all admissible values of α and δ.

Evaluating second-period equilibrium appropriation at fines f_i^{AO} and f_j^{AO}, yields

$$e_i^{AO} = \frac{\theta(18+\delta-3A)}{4\delta}.$$

Similarly, evaluating first-period equilibrium appropriation at fines f_i^{AO} and f_j^{AO}, yields

$$x_i^{AO} = \frac{\theta\left(6+\delta-A\right)\left[\delta(1+2g)-18+3A\right]}{8\delta^2}.$$

9.5 *Proof of Lemma 3*

Third stage. In the third stage, fisherman i's maximization problem is

$$\max_{x_i\geq 0} \quad \pi_i^{2,R} = x_i - \frac{x_i(x_i+x_j)}{\theta(1+g)-E} - \beta\frac{F}{2}(x_i+x_j-\hat{e})$$

Differentiating with respect to x_i, yields

$$1+\frac{2x_i+x_j}{\theta(1+g)-E}-\beta\frac{F}{2}=0$$

Solving for x_i, we obtain fisherman i's best response function

$$x_i(x_j)=\begin{cases}\frac{1}{4}\left(2-\beta F\right)\left[\theta(1+g)-E\right]-\frac{1}{2}x_j & \text{if } x_j<\frac{1}{2}\left(2-\beta F\right)\left[\theta(1+g)-E\right]\\ 0 & \text{otherwise.}\end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for x_i and x_j, we obtain second-period equilibrium appropriation

$$x_i^R(E)=\frac{(2-\beta F)[\theta(1+g)-E]}{6}$$

which is positive if $F<\frac{2}{\beta}$.

Second stage. Fisherman i anticipates $x_i^R(E)$ and $x_j^R(E)$, and solves the following problem

$$\max_{x_i\geq 0}\quad \pi_i^{1,R}+\delta\pi_i^{2,R}(x_i^R(E),x_j^R(E))$$

Differentiating with respect to e_i, yields

$$\frac{\theta(2-\beta F)(9-\delta(1-2\beta F)-18(2e_i+e_j)}{18\theta}=0$$

Solving for e_i, we obtain fisherman i's best response function

$$e_i(e_j)=\begin{cases}\frac{\theta}{36}(2-\beta F)(9-\delta(1-2\beta F))-\frac{1}{2}e_j, \text{ if } e_j<\frac{\theta}{18}(2-\beta F)(9-\delta(1-2\beta F))\\ 0 \quad \text{otherwise.}\end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for e_i and e_j, we obtain first-period equilibrium appropriation

$$e_i^R=\frac{\theta}{54}(2-\beta F)(9-\delta(1-2\beta F))$$

which are positive if $\beta<\frac{2}{F}$ and increasing in the abundance of the initial stock, θ.

First stage. The R chooses an aggregate quota and fine that maximize joint profits, as follows

$$\max_{\widehat{e},F\geq 0}\quad \left[\pi_i^{1,R}+\delta\pi_i^{2,R}\left(x_i^R(E),x_j^R(E)\right)\right] \\ +\left[\pi_j^{1,R}+\delta\pi_j^{2,R}\left(x_i^R(E),x_j^R(E)\right)\right]$$

Similar than before, the R finds the first-period socially optimal appropriation levels, e_i^{SO} and e_j^{SO}, and sets the quota $\hat{e}$ so that $\hat{e} = E^{SO} = e_i^{SO} + e_j^{SO}$. Then, the R identifies the fine F that induces both fishermen to appropriate at the socially optimal level E^{SO}. To find the first-period socially optimal appropriation levels, the R solves

$$\max_{e_i, e_j \geq 0} \quad \left[e_i - \frac{e_i(e_i + e_j)}{\theta} + \delta \pi_i^{2,R} \left(x_i^R(E), x_j^R(E) \right) \right] + \left[e_j - \frac{e_j(e_i + e_j)}{\theta} + \delta \pi_j^{2,R} \left(x_i^R(E), x_j^R(E) \right) \right]$$

Differentiating with respect to e_i and e_j and solving, yields

$$\frac{\theta[\delta(\beta F - 2)(\beta F + 1) + 9] - 18(e_i + e_j)}{9\theta} = 0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$\hat{e} = e_i^{SO} = \frac{\theta[9 + \delta(\beta F - 2)(\beta F + 1)]}{36}.$$

Setting it equal to the equilibrium first-period appropriation, we obtain $e_i^{SO} = e_i^R$, or

$$\frac{\theta[9 + \delta(\beta F - 2)(\beta F + 1)]}{36} = \frac{\theta}{54}(2 - \beta F)(9 - \delta(1 - 2\beta F))$$

which, solving for fine F, yields

$$F^R = \frac{(13\delta - 18) + 3C}{14\delta\beta}.$$

where $C \equiv [36 + \delta(25\delta - 24)]^{1/2}$, which is positive for all β and δ values greater than zero. Inserting this result into $e_i^{SO}(E)$, we find that first-period equilibrium appropriation is

$$e_i^R = \frac{\theta\left[3(6 - C) + \delta\left(37 - 5\delta + C\right)\right]}{196\delta},$$

Then, evaluating second-period equilibrium appropriation, x_i^R, at penalty F^R, yields

$$x_i^R = \frac{\theta(C - 5\delta - 6)[\delta(C - 5\delta - 98g - 61) - 3(C - 6)]}{2744\delta^2}.$$

which is positive for all admissible values, since C's lower bound. is 6 when δ is zero and its upper bound is around 6.08 when δ is one.

9.6 *Proof of Lemma 4*

Fourth stage. In the fourth stage, fisherman i's maximization problem is

$$\max_{x_i} \quad \pi_i^{2nd} = x_i - \frac{x_i(x_i + x_j)}{\theta(1+g) - E} - \alpha \left[f_i(x_i - \overline{e}_i) - f_j(x_j - \overline{e}_j) \right] - \beta \frac{F}{2}(x_i + x_j - \hat{e})$$

Differentiating with respect to e_i, we obtain

$$1 - \frac{2x_i + x_j}{\theta(1+g) - E} - \alpha f_i - \frac{\beta F}{2} = 0.$$

Solving for x_i, we obtain fisherman i's best response function

$$x_i(x_j) = \begin{cases} \frac{[\theta(1+g)-E](2-2\alpha f_i - \beta F)}{4} - \frac{x_j}{2} \text{ if } x_j < \frac{1}{2}[\theta(1+g) - E]\,(2 - 2\alpha f_i - \beta F) \\ 0 \text{ otherwise.} \end{cases}$$

Simultaneously solving for x_i and x_j, we find the equilibrium extraction

$$x_i(f_i, f_j, F) = \frac{[\theta(1+g) - E]\,[2 - \beta F - 2\alpha(2f_i - f_j)]}{6}$$

which increases in the available stock at the beginning of the second period, $\theta(1+g) - E$, and in his rival's penalty, f_j. However, second-period appropriation decreases in fisherman i's penalty, f_i and the expected fine from the regulator, βF.

Third stage. Fisherman i anticipates equilibrium second-period profits, $\pi_i^{1st}(x_i^*, x_j^*)$, and solves for the first period as follows

$$\max_{e_i \geq 0} \ \pi_i^{1,B} = \left[e_i - \frac{e_i(e_i + e_j)}{\theta} - \alpha \left[f_i(e_i - \overline{e}_i) - f_j(e_j - \overline{e}_i) \right] - \beta \frac{F}{2}(e_i + e_j - \hat{e}) \right] + \delta \pi_i^{2,B}(x_i^B, x_j^B)$$

Differentiating with respect to x_i, yields

$$\frac{(2 - \beta F)\left[9 + \delta\left(2\beta F - 1\right)\right]\theta - 36e_i - 18e_j - \alpha\theta \left[\begin{array}{c} f_i\left(18 - 8\delta - 2\alpha\delta f_j + \beta\delta F\right) \\ +\delta f_j\left(10(1 - \alpha f_j) + \beta F\right) + 8\alpha\delta f_i^2 \end{array} \right]}{18\theta} = 0$$

Solving for e_i, we obtain fisherman i's best response function

$$e_i(e_j) = \begin{cases} \dfrac{\theta(2-\beta F)[9+\delta(2\beta F-1)] - \alpha\theta \left[\begin{array}{c} f_i\left(18 - 8\delta - 2\alpha\delta f_j + \beta\delta F\right) \\ +\delta f_j\left(10(1 - \alpha f_j) + \beta F\right) + 8\alpha\delta f_i^2 \end{array} \right]}{36} - \dfrac{e_j}{2}, \\ \text{if } e_j < \dfrac{\theta(2-\beta F)[9+\delta(2\beta F-1)] - \alpha\theta \left[\begin{array}{c} f_i\left(18 - 8\delta - 2\alpha\delta f_j + \beta\delta F\right) \\ +\delta f_j\left(10(1 - \alpha f_j) + \beta F\right) + 8\alpha\delta f_i^2 \end{array} \right]}{18} \\ 0 \quad \text{otherwise.} \end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for e_i and e_j, we obtain first-period equilibrium appropriation

$$e_i^B = \frac{\theta\left[(2-\beta F)(\delta(2\beta F-1)+9)+\alpha\left(\begin{array}{c} 28\alpha\delta f_j^2 - f_i\left(26\alpha\delta f_i+\delta(\beta F-26)+36\right) \\ +f_j\left(18-\delta(28+\beta F)+2\alpha\delta f_i\right)+18) \end{array}\right)\right]}{54}$$

which are positive if and only if $\alpha \notin (\underline{\alpha}_2, \overline{\alpha}_2)$, where cutoffs $\underline{\alpha}_2$ and $\overline{\alpha}_2$ are

$$\underline{\alpha}_2 = \frac{f_i(\delta(26-\beta F)-36)-f_j(\delta(\beta F+28)-18)-H}{4\delta\left(13f_i-14f_j\right)\left(f_i+f_j\right)} \quad \text{and}$$

$$\overline{\alpha}_2 = \frac{f_i(\delta(26-\beta F)-36)-f_j(\delta(\beta F+28)-18)+H}{4\delta\left(13f_i-14f_j\right)\left(f_i+f_j\right)}$$

where

$$H \equiv \left[\begin{array}{c} \left(f_i(\delta(\beta F-26)+36)+f_j(\delta(\beta F+28)-18)\right)^2 \\ -8\delta(\beta F-2)\left(13f_i-14f_j\right)\left(f_i+f_j\right)\left(\delta(2\beta F-1)+9\right) \end{array}\right]^{1/2}$$

Second Stage. The AO chooses quotas and fines that maximize joint profits for both periods, as follows.

$$\max_{\overline{e}_i,\overline{e}_j,f_i,f_j\geq 0} \left[\pi_i^{1,AO}+\delta\pi_i^{2,AO}\left(x_i^{AO}(E),x_j^{AO}(E)\right)\right] + \left[\pi_j^{1,AO}+\delta\pi_j^{2,AO}\left(x_i^{AO}(E),x_j^{AO}(E)\right)\right]$$

Differentiating with respect to e_i, yields

$$\frac{\theta\left[\alpha\delta\left(f_i+f_j\right)\left(\alpha\left(f_i+f_j\right)+2\beta F-1\right)+\delta(\beta F-2)(\beta F+1)+9\right]-18(e_i+e_j)}{9\theta}=0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$e_i^B = \frac{1}{36}\theta\left[\alpha\delta\left(f_i+f_j\right)\left(\alpha\left(f_i+f_j\right)+2\beta F-1\right)+\delta(\beta F-2)(\beta F+1)+9\right].$$

Setting it equal to the equilibrium first-period appropriation, $e_i(f_i, f_j)$, we find

$$f_i^B(F) = \frac{\delta-18-8\delta\beta F+3\sqrt{36+24\delta\beta F+(\delta+2\delta\beta F)^2}}{4\delta\alpha}.$$

which is positive for α and δ admissible values.

First stage. The R chooses an aggregate quota and fine that maximize joint profits for both periods, as follows.

$$\max_{\widehat{e},F\geq 0} \pi_o = \left[e_i - \frac{e_i(e_i+e_j)}{\theta} + \delta\pi_i^{2,R}\left(x_i^R(E), x_j^R(E)\right)\right] + \left[e_j - \frac{e_j(e_i+e_j)}{\theta} + \delta\pi_j^{2,R}\left(x_i^R(E), x_j^R(E)\right)\right]$$

Similar than before, we first find the socially optimal appropriation. In particular, differentiating with respect to e_i, yields

$$\frac{\delta + \beta\delta F\delta\left(2\beta\delta F + 12 + \delta - \sqrt{(\delta+2\beta\delta F)^2 + 24\beta\delta F + 36}\right) - 3\left(\sqrt{(\delta+2\beta\delta F)^2+24\beta\delta F+36} - 6\right)}{\delta} - \frac{2(e_i+e_j)}{\theta} = 0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$e_i^B = \frac{\theta\left[\delta + \beta\delta F\left(\delta + 2\beta\delta F - \sqrt{(\delta+2\beta\delta F)^2+24\beta\delta F+36} + 12\right) - 3\left(\sqrt{(\delta+2\beta\delta F)^2+24\beta\delta F+36} - 6\right)\right]}{4\delta}$$

Setting it equal to the equilibrium first-period appropriation found in the second stage, e_i^B, but evaluated at $f_i^B(F) = \frac{(\delta - 8\beta\delta F - 18) + 3\sqrt{(\delta+2\beta\delta F)^2+24\beta\delta F+36}}{4\alpha\delta}$ and solving for F, yields a continuum of solutions for F^B, such as $F^B = \frac{2\delta-5}{2\beta\delta}$.

$$f_i^B = \frac{2 - 7\delta + 3D}{4\alpha\delta},$$

$$e_i^B = \frac{\left(1+\delta+6\delta^2 - D(1+2\delta)\right)\theta}{8\delta}, \text{ and}$$

$$x_i^B = \frac{(1+3\delta - D)\left[\delta(3+4g-6\delta+2D) - D - 1\right]\theta}{16\delta^2}.$$

where $D \equiv (3\delta - 1)$.

9.7 *Proof of Corollary 1*

First-period appropriation. Note that section assumes $\delta = 1$. When only the AO is present, we obtain

$$\begin{aligned} e_i^{AO,IN} - e_i^{AO,F} &= \frac{\left(19 - 3\sqrt{37}\right)\theta}{4} - \frac{3\theta}{16} \\ &= \frac{\left(73 - 12\sqrt{37}\right)\theta}{16} \end{aligned}$$

which is positive for all parameter values. Therefore, $e_i^{AO,IN}$ is greater than $e_i^{AO,F}$.

When only the R is present, we find that

$$\begin{aligned} e_i^{R,IN} - e_i^{R,F} &= \frac{\theta\left[\delta\left(32+\sqrt{37}\right)-3(\sqrt{37}-6)\right]}{196} - \frac{3\theta}{16} \\ &= \frac{\left((4\sqrt{37}-19)-12\left(\sqrt{37}-6\right)\right)\theta}{784} \end{aligned}$$

which is also positive for all admissible values of θ and δ. Therefore, $e_i^{R,IN}$ is greater than $e_i^{R,F}$.

Finally, $e_i^{B,IN}$ is greater than $e_i^{B,F}$ for all parameter values. That is

$$\begin{aligned} e_i^{B,IN} - e_i^{B,F} &= \frac{\left(19-3\sqrt{37}\right)\theta}{4} - \frac{3\theta}{16} \\ &= \frac{\left(73-12\sqrt{37}\right)\theta}{16} \end{aligned}$$

Second-period appropriation. When only the AO is present, we obtain

$$\begin{aligned} x_i^{AO,F} - x_i^{AO,IN} &= \left[\frac{\theta(8g+5)}{32}\right] - \left[\frac{\theta\left(7-\sqrt{37}\right)\left[(1+2g)-18+3\sqrt{37}\right]}{8}\right] \\ &= \frac{\theta(925-152\sqrt{37}+8g(\sqrt{37}-6))}{32} \end{aligned}$$

which is positive for all admissible parameter values. Therefore, $x_i^{AO,F}$ is greater than $x_i^{AO,IN}$.

When only the R is present, we find that

$$\begin{aligned} x_i^{R,F} - x_i^{R,IN} &= \left[\frac{\theta(8g+5)}{32}\right] - \left[\frac{\theta(\sqrt{37}-11)[(\sqrt{37}-98g-66)-3(\sqrt{37}-6)]}{2744}\right] \\ &= \frac{\theta(2744(8g+5)-32(\sqrt{37}-11)(18-2\sqrt{37}-(66+98g)))}{87808} \end{aligned}$$

which is positive for all admissible parameter values. This implies that $x_i^{R,F}$ is greater than $x_i^{R,IN}$.

Finally, $x_i^{B,F}$ is greater than $x_i^{B,IN}$ for all parameter values. That is,

$$\begin{aligned} x_i^{B,F} - x_i^{B,IN} &= \left[\frac{\theta(8g+5)}{32}\right] - \left[\frac{\theta\left(7-\sqrt{37}\right)\left[(1+2g)-18+3\sqrt{37}\right]}{8}\right] \\ &= \frac{\theta(925-152\sqrt{37}+8g(\sqrt{37}-6))}{32} \end{aligned}$$

9.8 *Proof of Corollary 2*

Comparing first-period inefficiencies (FPI) between the R and the AO, $FPI^R - FPI^{AO} = (e_i^{R,IN} - e_i^{R,F}) - (e_i^{AO,IN} - e_i^{AO,F})$, we obtain

$$\begin{aligned} FPI^R - FPI^{AO} &= \left[\frac{\left(\left(4\sqrt{37}-19\right)-12\left(\sqrt{37}-6\right)\right)\theta}{784}\right] - \left[\frac{\left(73-12\sqrt{37}\right)\theta}{16}\right] \\ &= \frac{\left(145\sqrt{37}-881\right)\theta}{196} \end{aligned}$$

which is positive for all θ admissible parameter values. Therefore, the FPI is larger with R than with AO. Similarly, since $FPI^{AO} = FPI^B$, then $FPI^R - FPI^B$ is also positive. Hence, $FPI^k \geq FPI^B$ for $k \in \{AO, R\}$.

Then, comparing second-period inefficiencies (SPI) between the R and the AO, $SPI^R - SPI^{AO} = (x_i^{R,F} - x_i^{R,IN}) - (x_i^{AO,F} - x_i^{AO,IN})$, we find that

$$\begin{aligned} SPI^R - SPI^{AO} &= \left[\frac{\theta(2744(8g+5)-32(\sqrt{37}-11)(18-2\sqrt{37}-(66+98g)))}{87808}\right] - \left[\frac{\theta(925-152\sqrt{37}+8g(\sqrt{37}}{32}\right. \\ &= \frac{\theta(3265\sqrt{37}-19836+49g(19-3\sqrt{37}))}{686} \end{aligned}$$

which is positive for all admissible parameter values. Therefore, the SPI is larger with R than with AO. In addition, since second-period inefficiency with AO and B coincide, $SPI^R > SPI^{AO} = SPI^B$.

9.9 *Proof of Lemma 5*

9.9.1 Only R is present

Fourth stage. In the fourth stage, every fisherman i solves for the same maximization problem as in the proof of Proposition 2, omitted here for compactness.

Third stage. The R chooses quotas and fines that maximize joint profits for the second period, as follows.

$$\max_{x_i, x_j \geq 0} \pi_o = \left[x_i - \frac{x_i\,(x_i+x_j)}{[\theta(1+g)-E]}\right] + \left[x_j - \frac{x_j\,(x_i+x_j)}{[\theta(1+g)-E]}\right] - d(x_i+x_j)$$

Differentiating with respect to x_i, yields

$$\frac{(1-d)\,[(1+g)\theta-E]-2(x_i+x_j)}{\theta(1+g)-E} = 0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$\tilde{x}_i^R(E) = \frac{(1-d)\,[\theta(1+g)-E]}{4}.$$

Setting it equal to the equilibrium second-period appropriation found above, $\tilde{x}_i^R(E)$, we find

$$T^{SO} = \frac{1+3d}{2\beta}.$$

which is positive for all β and d values.

Second stage. In the second stage, every fisherman i anticipates equilibrium second-period appropriations, $\tilde{x}_i^R(E)$ and $\tilde{x}_j^R(E)$, and solves

$$\max_{e_i \geq 0} \quad \pi_i^{1,R} + \delta \pi_i^{2,R}\left(\tilde{x}_i^R(E), \tilde{x}_j^R(E)\right)$$

Differentiating with respect to e_i, yields

$$\frac{\theta\left[8 - \delta(1-d^2) - 4\beta F\right] - 8(2e_i + e_j)}{8\theta} = 0$$

Then, solving for e_i, we obtain a best response function

$$e_i(e_j) = \begin{cases} \frac{\theta\left[8-\delta(1-d^2)-4\beta F\right]}{16} - \frac{1}{2}e_j, & \text{if } e_j < \frac{\theta}{8}\left[8 - \delta(1-d^2) - 4\beta F\right], \\ 0 \quad \text{otherwise.} \end{cases}$$

Simultaneously solving for e_i and e_j in the above best response functions, we obtain first-period equilibrium appropriation

$$\tilde{e}_i^* = \frac{\theta[8 - \delta(1-d^2) - 4\beta F]}{24}$$

First stage. The R chooses quotas and fine that maximize joint profits, as follows.

$$\max_{e_i, e_j \geq 0} \quad \left[e_i - \frac{e_i(e_i+e_j)}{\theta} + \delta \pi_i^{2,R}\left(\tilde{x}_i^R(E), \tilde{x}_j^R(E)\right)\right]$$
$$+ \left[e_j - \frac{e_j(e_i+e_j)}{\theta} + \delta \pi_j^{2,R}\left(\tilde{x}_i^R(E), \tilde{x}_j^R(E)\right)\right] - d(e_i + e_j)$$

where $E = e_i + e_j$. Then, differentiating with respect to e_i, yields

$$\frac{(e_i+e_j)\left[\theta(1-d)(4-\delta(1-d)) - 4e_i - 4e_j\right]}{4\theta} + \frac{\delta\theta}{4}(1-d)^2(1+g) = 0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$\tilde{e}_i^{R,F} = \frac{\theta(1-d)(4-\delta(1-d))}{16}.$$

Setting it equal to the equilibrium first-period appropriation, e_i^*, we obtain

$$F^* = \frac{4 + \delta + d(12 - \delta(6-5d))}{8\beta}$$

which is increasing in d if $d > \frac{3(\delta-2)}{5\delta}$, but $\frac{3(\delta-2)}{5\delta} < 0$ for all values of δ, entailing that condition $d > \frac{3(\delta-2)}{5\delta}$ always holds. Therefore, fee F^* is unambiguously increasing in d.

Inserting this result into $x_i^{R,F}(E)$, we find that second-period equilibrium appropriation is

$$\tilde{x}_i^{R,F} = \frac{\theta(1-d)\left[4+8g+\delta+d(4-\delta(2-d))\right]}{32}$$

Evaluating the above results at $d = 0$, we obtain

$$\tilde{e}_i = \frac{\theta(4-\delta)}{16}, \ \tilde{x}_i = \frac{\theta(4+8g+\delta)}{32} \ \text{ and } \ F = \frac{4+\delta}{8\beta}$$

which, as expected, coincide with our results in Proposition 2b.

9.9.2 Both R and AO are present

Sixth stage. In this stage, every fisherman i solves for the same maximization problem as in the proof of Proposition 2, omitted here for compactness.

Fifth stage. The AO chooses quotas and fines that maximize joint profits for the second period, as follows.

$$\max_{x_i,x_j} \left[x_i - \frac{x_i\,(x_i+x_j)}{[\theta(1+g)-E]} - \beta\frac{T}{2}(x_i+x_j-\hat{x})\right] + \left[x_j - \frac{x_j\,(x_i+x_j)}{[\theta(1+g)-E]} - \beta\frac{T}{2}(x_i+x_j-\hat{x})\right]$$

Differentiating with respect to x_i, yields

$$\frac{[\theta(1+g)-E]\,(1-\beta T) - 2x_i - 2x_j}{\theta(1+g)-E} = 0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$\tilde{x}_i^B = \frac{[\theta(1+g)-E]\,(1-\beta T)}{4}.$$

Setting it equal to the equilibrium second-period appropriation found above, $x_i(f_i, f_j, F)$, we obtain

$$t_i^B = \frac{1+\beta T}{4\alpha}.$$

which is positive for all α values.

Fourth stage. The R chooses quotas and fines that maximize joint profits for the second period, as follows.

$$\max_{x_i,x_j\geq 0} \left[x_i - \frac{x_i\,(x_i+x_j)}{[\theta(1+g)-E]}\right] + \left[x_j - \frac{x_j\,(x_i+x_j)}{[\theta(1+g)-E]}\right] - d(x_i+x_j)$$

Differentiating with respect to x_i, yields

$$\frac{(1-d)\left[\theta(1+g)-E\right]-2x_i-2x_j}{\theta(1+g)-E}=0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$\tilde{x}_i^{B,F}=\frac{(1-d)\left[\theta(1+g)-E\right]}{4}.$$

Setting it equal to the equilibrium second-period appropriation found above, $x_i^{B,F}$, we obtain $T=\frac{d}{\beta}$, which implies that the fine induces compliance.

Third stage. Fisherman i anticipates equilibrium second-period profits, $\pi_i^2(x_i^*,x_j^*)$, and solves the following problem

$$\max_{e_i}\ \pi_i^{1,B}=\left[e_i-\frac{e_i(e_i+e_j)}{\theta}-\alpha\left[f_i(e_i-\overline{e}_i)-f_j(e_j-\overline{e}_j)\right]-\beta\frac{F}{2}(e_i+e_j-\hat{e})\right]+\delta\pi_i^{2,B}(x_i^*,x_j^*)$$

where the terms in brackets denote first-period profits and the second-period profits are evaluated at first-period appropriation, $E\equiv e_i+e_j$.

Differentiating with respect to e_i, yields

$$\frac{\theta\left[8-\delta(1-d^2)-8\alpha f_i-4\beta F\right]-8(2e_i+e_j)}{8\theta}=0$$

Then, solving for e_i, we obtain a best response function

$$e_i(e_j)=\begin{cases}\frac{1}{16}\theta\left[8-\delta(1-d^2)-8\alpha f_i-4\beta F\right]-\frac{1}{2}e_j, & \text{if } e_j<\frac{1}{8}\theta\left[8-\delta(1-d^2)-8\alpha f_i-4\beta F\right],\\ 0 & \text{otherwise.}\end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for e_i and e_j in the above best response functions, we obtain first-period equilibrium appropriation.

$$e_i=\frac{\theta\left[8-\delta(1-d^2)-4\beta F-8\alpha(f_i+2f_j)\right]}{24}$$

Second stage. The AO chooses quotas and fines that maximize joint profits for both period, as follows.

$$\max_{e_i,e_j\geq 0}\ \left[e_i-\frac{e_i(e_i+e_j)}{\theta}-\beta\frac{F}{2}\left(e_i+e_j-e_r\right)+\delta\pi_i^{2,B}\left(\tilde{x}_i^B(E),\tilde{x}_j^B(E)\right)\right]$$
$$+\left[e_j-\frac{e_j(e_i+e_j)}{\theta}-\beta\frac{F}{2}\left(e_i+e_j-e_r\right)+\delta\pi_j^{2,B}\left(\tilde{x}_i^B(E),\tilde{x}_j^B(E)\right)\right]$$

Differentiating with respect to e_i, yields

$$\frac{\theta\left[4+\left(d^2-1\right)\delta-4\beta F\right]-8(e_i+e_j)}{4\theta}=0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$\tilde{e}_i^B(F)=\frac{1}{16}\theta\left[4-\delta(1-d^2)-4\beta F\right].$$

Setting it equal to the equilibrium first-period appropriation, $\tilde{e}_i^*$, we obtain

$$f_i^B(F)=\frac{4+4\beta F+\delta(1-d^2)}{16\alpha}.$$

which is positive for all parameter values.

First period. The R chooses an aggregate quota and fine that maximize joint profits for bot periods, as follows.

$$\begin{aligned}\max_{e_i,e_j\geq 0}\ \pi_o \ &= \ \left[e_i-\frac{e_i(e_i+e_j)}{\theta}+\delta\pi_i^{2,R}\left(\tilde{x}_i^R(E),\tilde{x}_j^R(E)\right)\right]-d(e_i+\delta x_i)\\ &+\left[e_j-\frac{e_j(e_i+e_j)}{\theta}+\delta\pi_j^{2,R}\left(\tilde{x}_i^R(E),\tilde{x}_j^R(E)\right)\right]-d(e_j+\delta x_j)\end{aligned}$$

Differentiating with respect to e_i, yields

$$\frac{\theta(1-d)[(d-1)\delta+4]-8(e_i+e_j)}{4\theta}=0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$\tilde{e}_i^{B,F}=\frac{\theta(1-d)(4-\delta(1-d))}{16}.$$

Setting it equal to the equilibrium first-period appropriation found above, $\tilde{e}_i^B$, we obtain

$$F^B=\frac{d\left[2-(1-d)\delta\right]}{2\beta}$$

which entails $f_i^B=\frac{d((d-2)\delta+4)+4+\delta}{16\alpha}$. Fine F^B is unambiguously increasing in d, and f_i^B is increasing in d if and only if $d>\frac{\delta-2}{\delta}$, where $\frac{\delta-2}{\delta}<0$ for all admissible values of δ. Therefore, the fine is unambiguously increasing in d.

Inserting these results into second-period appropriation, $\tilde{x}_i^B(E)$, we find that

$$\tilde{x}_i^{B,F}=\frac{\theta(1-d)(4+8g+\delta+d(4-\delta(2-d))}{32}$$

Evaluating the above results at $d = 0$, we obtain

$$\tilde{e}_i = \frac{\theta(4-\delta)}{16}, \ \ \tilde{x}_i = \frac{\theta(\delta+8g+4)}{32}, \ \ F = 0, \ \ f_i = \frac{4+\delta}{16\alpha} \ \ \text{and} \ \ \ t_i = \frac{1}{4\alpha}$$

which, as expected, coincides with our results in Proposition 2c.

9.10 *Proof of Lemma 6*

9.10.1 Only R is present

Third stage. In this stage, every fisherman i solves for the same maximization problem as in the proof of Proposition 2, omitted here for compactness.

Second stage. Fisherman i anticipates equilibrium second-profits appropriations, $\tilde{x}_i^R(E)$ and $\tilde{x}_j^R(E)$, and solves the following problem

$$\max_{x_i \geq 0} \ \ \pi_i^{1,R} + \delta \pi_i^{2,R}(\tilde{x}_i^R(E), \tilde{x}_j^R(E))$$

Differentiating with respect to e_i and solving for e_i, we obtain a best response function

$$e_i(e_j) = \begin{cases} \frac{1}{36}[\theta(2-\beta F)(\delta(2\beta F-1)+9)] - \frac{1}{2}e_j, \ \text{if } e_j < \frac{\theta(2-\beta F)(\delta(2\beta F-1)+9}{18} \\ 0 \ \ \text{otherwise.} \end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for e_i and e_j in the above best response functions, we obtain first-period equilibrium appropriation

$$\tilde{e}_i = \frac{\theta(2-\beta F)[\delta(2\beta F-1)+9]}{54}$$

which is positive if $\beta < \frac{2}{F}$.

First stage. The regulator finds the first-period socially optimal aggregate appropriation, $E = e_i + e_j$, sets it as quota. Then, the regulator identifies the fine F that induces both fishermen to appropriate at the socially optimal levels $E^{SO} = e_i^{SO} + e_j^{SO}$. In particular, the regulator solves,

$$\begin{aligned} \max_{e_i, e_j \geq 0} \ \ \pi_o \ \ &= \ \ \left[e_i - \frac{e_i(e_i+e_j)}{2\theta} + \delta\pi_i^{2,R}\left(\tilde{x}_i^R(E), \tilde{x}_j^R(E)\right)\right] - d(e_i + \delta x_i) \\ &+ \left[e_j - \frac{e_j(e_i+e_j)}{2\theta} + \delta\pi_j^{2,R}\left(\tilde{x}_i^R(E), \tilde{x}_j^R(E)\right)\right] - d(e_j + \delta x_j) \end{aligned}$$

Differentiating the regulator's problem with respect to e_i, and solving for e_i yields

$$e_i = \frac{\theta(\delta(2-\beta F)(3d-\beta F-1) - 9d + 9)}{18} - e_j = 0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$\tilde{e}_i^{R,IN} = \frac{\theta(\delta(2-\beta F)(3d-\beta F-1)-9d+9)}{36}.$$

Setting it equal to the equilibrium first-period appropriation, $e_i(f_i, f_j)$, we find

$$F^* = \frac{\delta(9d+13)-18+3G}{14\beta\delta}$$

where $G \equiv \left[\delta\left(\delta(5-3d)^2+48d-24\right)+36\right]^{1/2}$. Fine F^* is positive for all β values, increasing in d, and the second-period appropriation in equilibrium is

$$\tilde{x}_i^{R,IN} = \frac{\theta((3d-5)\delta+G-6)(18-3G+\delta(G-5\delta-98g-61))}{2744\delta^2}.$$

when $d=0$ the above results coincide with those in Lemma 3.

9.10.2 Both R and AO are present

Fourth stage, fisherman i's maximization problem for the second period is

$$\max_{x_i} \quad \pi_i^{2nd} = x_i - \frac{x_i(x_i+x_j)}{[\theta(1+g)-E]} - \alpha\left[f_i(x_i-\overline{e}_i)-f_j(x_j-\overline{e}_j)\right] - \beta\frac{F}{2}(x_i+x_j-\hat{e})$$

Differentiating with respect to x_i, we obtain

$$\frac{[\theta(1+g)-E](2-\beta F)-2(2x_i+x_j)}{2[\theta(1+g)-E]} - \alpha f_i = 0.$$

Then, solving for x_i, we obtain the following best response function.

$$x_i(x_j) = \begin{cases} \frac{[\theta(1+g)-E](2-2\alpha f_i-\beta F)}{4} - \frac{x_j}{2} & \text{if } x_j < \frac{[\theta(1+g)-E](2-2\alpha f_i-\beta F)}{2} \\ 0 & \text{otherwise.} \end{cases}$$

Simultaneously solving for x_i and x_j, we obtain the equilibrium extraction,

$$x_i(f_i, f_j, F) = \frac{[\theta(1+g)-E](2-2\alpha(2f_i-f_j)-\beta F)}{6}$$

which is positive if $\alpha < \frac{2-\beta F}{2(2f_i-f_j)}$.

Third stage. Fisherman i anticipates equilibrium second-period profits, $\pi_i^{1st}(\tilde{x}_i^*, \tilde{x}_j^*)$, and solves the following problem for the first period

$$\max_{e_i} \ \pi_i^{2nd} = \left[e_i - \frac{e_i(e_i+e_j)}{\theta} - \alpha\left[f_i(x_i-\overline{e}_i)-f_j(x_j-\overline{e}_j)\right] - \beta\frac{F}{2}(e_i+e_j-\hat{e})\right] + \delta\pi_i^{2nd}(\tilde{x}_i^*, \tilde{x}_j^*)$$

where the terms in brackets denote first-period profits and the second-period profits are evaluated at first-period appropriation, $E \equiv e_i + e_j$.

Differentiating with respect to e_i, and solving for e_i, we obtain the following best response function

$$e_i(e_j) = \begin{cases} \frac{\theta((2-\beta F)(9-\delta(1-2\beta F))-\alpha\left(f_i(18-8\delta-\delta(2\alpha f_j+\beta F))+\delta f_j(\beta F-10\alpha f_j+10)+8\delta\alpha f_i^2\right))}{36} - \frac{e_j}{2}, \\ \text{if } e_j < \frac{\theta((2-\beta F)(9-\delta(1-2\beta F))-\alpha\left(f_i(18-8\delta-2\delta\alpha f_j+\delta\beta F)+\delta f_j(\beta F-10\alpha f_j+10)+8\delta\alpha f_i^2\right))}{18} \\ 0 \quad \text{otherwise.} \end{cases}$$

Fisherman j has a symmetric best response function. Simultaneously solving for e_i and e_j in the above for best response functions, we obtain first-period equilibrium appropriation

$$e_i = \frac{\theta[(2-\beta F)(9-\delta(1-2\beta F)) - \alpha \begin{pmatrix} f_i\left(36+\delta(\beta F-26)\right)+26\delta\alpha f_i) - \\ f_j\left(18-\delta(\beta F+28)+2\delta\alpha f_i\right)+28\delta\alpha f_j^2 \end{pmatrix}]}{54}$$

Second Stage. The artisanal organization chooses quotas and fines that maximize joint profits. Differentiating the artisanal's organization problem with respect to e_i, and solving by e_i, yields

$$e_i = \frac{\theta(9+\delta(\beta F-2)(\beta F+1)+\delta\alpha\left(f_i+f_j\right)\left[\alpha\left(f_i+f_j\right)+2\beta F-1\right])}{18} - e_j = 0$$

The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$e_i = \frac{\theta\left[9+\delta(\beta F-2)(\beta F+1)+\delta\alpha\left(f_i+f_j\right)\left(\alpha\left(f_i+f_j\right)+2\beta F-1\right)\right]}{36}.$$

Setting it equal to the equilibrium first-period appropriation, $e_i(f_i, f_j)$, we find

$$f_i = \frac{(\delta-18-8\delta\beta F)+3\sqrt{36+24\delta\beta F+(\delta+2\delta\beta F)^2}}{4\delta\alpha}.$$

which is positive for all $\alpha > 0$ values.

First Stage. The regulator chooses an aggregate quota and fine that maximize joint profits for both periods, including the environmental damage d, as follows

$$\begin{aligned} \max_{e_i, e_j \geq 0} \pi_o \quad = \quad & \left[e_i - \frac{e_i(e_i+e_j)}{\theta} + \delta\pi_i^{2,R}\left(\tilde{x}_i^R(E), \tilde{x}_j^R(E)\right)\right] - d(e_i+\delta x_i) \\ & + \left[e_j - \frac{e_j(e_i+e_j)}{\theta} + \delta\pi_j^{2,R}\left(\tilde{x}_i^R(E), \tilde{x}_j^R(E)\right)\right] - d(e_j+\delta x_j) \end{aligned}$$

Then, differentiating with respect to e_i and e_j and solving, we obtain the following result.

$$e_i = \frac{\theta(2\delta+d\delta(4+\delta(1+2\beta F)-\Phi)+2\delta\beta F(12+\delta(1+2\beta F)-\Phi)-24(\Phi-6))}{4\delta} - e_j$$

where $\Phi \equiv \sqrt{36+24\delta\beta F+(\delta+2\delta\beta F)^2}$. The first order conditions are symmetric across fishermen. Invoking symmetry, we obtain

$$\widetilde{e}^{B,IN} = \frac{\theta(36-6\Phi+\delta(2+d(4+\delta(1+2\beta F)-\Phi)+2\beta F(12+\delta(1+2\beta F)-\Phi)))}{8\delta}$$

Setting it equal to the equilibrium first-period appropriation, $e_i^{B,IN}$, we find that $F^{B,IN}=\frac{2\delta-5}{2\beta\delta}$. However, since $\frac{2\delta-5}{2\beta\delta}<0$ for all admissible parameters, $F^{B,IN}=0$, implying that

$$\widetilde{e}^{B,IN} = \frac{\theta\left[6(1-A)+\delta\left(2+d\left(4+\delta-A\right)\right)\right]}{8\delta}$$

and satisfies $\frac{\partial\widetilde{e}^{B,IN}}{\partial d}=\frac{\theta(4+\delta-A)}{8}$, which is negative for all values of δ, entailing that $\widetilde{e}^{B,IN}$ is unambiguously decreasing in d.

Therefore, the organization's fine is $f_i^{B,IN}=\frac{\delta+3(A-6)}{4\alpha\delta}$. Finally, evaluating our results on $\widehat{x}_i(f_i,f_j,F)$ we obtain

$$\widetilde{x}_i^{B,IN} = \frac{\theta(6+\delta-A)\left[A-36+\delta\left(2+4g+d\left(A-4-\delta\right)\right)\right]}{16\delta^2},$$

which satisfies $\frac{\partial\widetilde{x}^{B,IN}}{\partial d}=\frac{\theta(6+\delta-A)(A-4-\delta)}{16\delta}$ which is positive for all values of δ, implying that $\widetilde{x}^{B,IN}$ is unambiguously increasing in d. Evaluating $\widetilde{e}^{B,IN}$ and $\widetilde{x}^{B,IN}$ at $d=0$, we find that the above results coincide with those in Lemma 4.

9.11 *Proof of Corollary 3*

First-period appropriation. When only the R is present, we obtain

$$\begin{aligned}\widetilde{FPI}^{R} &= \tilde{e}_i^{R,IN}-\tilde{e}_i^{R,F}=\frac{\theta(\delta(2-\beta F)(3d-\beta F-1)-9d+9)}{36}-\frac{\theta(1-d)(4-\delta\left(1-d\right))}{16}.\\ &= \frac{\delta\theta(1+3d-2\beta F)^2}{144}\end{aligned}$$

the numerator is positive for all admissible values of θ, F and d. Therefore, $\tilde{e}_i^{R,IN}>\tilde{e}_i^{R,F}$, entailing that $\widetilde{FPI}^{R}>0$.

When only AO is present, first-period appropriation levels in the inflexible and flexible regimes, $\tilde{e}_i^{AO,IN}$ and $\tilde{e}_i^{AO,F}$, coincide with those found in Section 5, that is, $\tilde{e}_i^{AO,IN}=e_i^{AO,IN}$ and $\tilde{e}_i^{AO,F}=e_i^{AO,F}$. As shown in Corollary 1, $e_i^{AO,IN}>e_i^{AO,F}$,

$$\begin{aligned}e_i^{AO,IN}-e_i^{AO,F} &= \frac{\theta(18+\delta-3\sqrt{36+\delta^2})}{4\delta}-\frac{\theta(4-\delta)}{16}\\ &= \frac{(72+\delta^2-12\delta\sqrt{36+\delta^2})\theta}{16}=\frac{(73-12\sqrt{37})\theta}{16}\end{aligned}$$

which is positive for all $\theta>0$ and $\delta=1$, since $e_i^{AO,IN}-e_i^{AO,F}=0.62\theta$. Therefore, $\tilde{e}_i^{AO,IN}>\tilde{e}_i^{AO,F}$, which implies that $\widetilde{FPI}^{AO} > 0$ in this regulatory setting too.

When both AO and R are present, the difference between first-period appropriation levels (evaluated at $\delta = 1$) is

$$\begin{aligned}\widetilde{FPI}^{B} &= \tilde{e}_i^{B,IN} - \tilde{e}_i^{B,F} \\ & \frac{\theta\left[38 - 6\sqrt{37} - d\left(\sqrt{37} - 5\right)\right]}{8} - \frac{\theta(1-d)(3+d)}{16} \\ &= \frac{\theta\left[73 - 12\sqrt{37} - d\left(12 - 2\sqrt{37} + d\right)\right]}{16}\end{aligned}$$

which is positive for all admissible values of θ and d. Therefore, $\tilde{e}_i^{B,IN} > \tilde{e}_i^{B,F}$, implying that $\widetilde{FPI}^{B} > 0$.

Second-period appropriation. When only the R is present, we find that (note that G evaluated at $\delta = 1$ simplifies to $G \equiv \left[37 + 18d + 9d^2\right]^{1/2}$)

$$\begin{aligned}\widetilde{SPI}^{R} &= \tilde{x}_i^{R,F} - \tilde{x}_i^{R,IN} \\ &= \frac{\theta(1-d)(5+8g+d(2+d))}{32} - \frac{\theta((3d-5)\delta + G - 6)(18 - 3G + \delta(G - 5\delta - 98g - 61))}{2744\delta^2} \\ &= \frac{\theta(1372(1-d)(5+d(2+d)+8g) + 32(G+3d-11)(24+\sqrt{37}+49g))}{43904}\end{aligned}$$

which is positive for all admissible values of g and d, therefore, $\widetilde{SPI}^{R} > 0$ and $\tilde{x}_i^{R,F} > \tilde{x}_i^{R,IN}$. When AO is present, we obtain that

$$\begin{aligned}\widetilde{SPI}^{AO} &= \tilde{x}_i^{AO,F} - \tilde{x}_i^{AO,IN} \\ &= \frac{\theta(5+8g)}{32} - \frac{(7-\sqrt{37})(2g - 17 + 3\sqrt{37})\theta}{8} \\ &= \frac{\theta(925 - 152\sqrt{37} + 8g(\sqrt{37} - 6))}{32}\end{aligned}$$

which is positive for all admissible parameter values. Therefore $\widetilde{SPI}^{AO} > 0$, which implies that $\tilde{x}_i^{AO,F} > \tilde{x}_i^{AO,IN}$.

When both AO and R are present, we obtain that

$$\begin{aligned}\widetilde{SPI}^{B} &= \tilde{x}_i^{B,F} - \tilde{x}_i^{B,IN} \\ &= \frac{\theta(1-d)\left[5+8g+d(2+d)\right]}{32} - \frac{\theta(6+\delta-A)\left[A - 36 + \delta\left(2+4g+d\left(A-4-\delta\right)\right)\right]}{16\delta^2} \\ &= \frac{\theta\left\{925 - 152\sqrt{37} + 8\left[\sqrt{37} - 6g + d\left(141 - 24\sqrt{37} - d(1+d) - 8g\right)\right]\right\}}{32}\end{aligned}$$

which is negative for all $d = \sqrt{37} - 6 \simeq 0.08$, but positive otherwise.

Under flexible policies, for first-period appropriation we obtain that

$$\begin{aligned}\tilde{e}_i^{AO,F} - \tilde{e}_i^{R,F} &= \frac{3\theta}{16} - \frac{\theta(1-d)(3+d)}{16} \\ &= \frac{(2d^2+4d-3)\theta}{16}\end{aligned}$$

which is positive for all $d > \frac{1}{2}$. In contrast, $\tilde{e}_i^{R,F} = \tilde{e}_i^{B,F}$ for all parameter values. Similarly, for second-period appropriation, we find that

$$\begin{aligned}\tilde{x}_i^{AO,F} - \tilde{x}_i^{B,F} &= \frac{\theta(5+8g)}{32} - \frac{\theta(1-d)\left[5+8g+d(2+d)\right]}{32} \\ &= \frac{\theta d(3+d+d^2+8g)}{32}\end{aligned}$$

which is positive for all admissible values of d and g. Hence, $\tilde{x}_i^{AO,F} > \tilde{x}_i^{B,F}$ and $\tilde{x}_i^{R,F} = \tilde{x}_i^{B,F}$ holds under all parameter values.

9.12 *Proof of Corollary 4*

Comparing $\widetilde{FPI}^R$ and $\widetilde{FPI}^{AO}$, we obtain that

$$\begin{aligned}\widetilde{FPI}^R - \widetilde{FPI}^{AO} &= \frac{\theta(1+3d-2\beta F)^2}{144} - \frac{(73{-}12\sqrt{37})\theta}{16} \\ &= \frac{((1+3d-2\beta F)^2 - 9(73{-}12\sqrt{37}))\theta}{144}\end{aligned}$$

note that $F = \frac{9d-5+3G}{14\beta}$ and $G \equiv \left[37+18d+9d^2\right]$. Hence, $\widetilde{FPI}^R - \widetilde{FPI}^{AO}$ is positive if and only if $d < 0.68$ and, thus, $\widetilde{FPI}^R > \widetilde{FPI}^{AO}$. Comparing $\widetilde{FPI}^R$ now against $\widetilde{FPI}^B$, we find that

$$\begin{aligned}\widetilde{FPI}^R - \widetilde{FPI}^B &= \frac{\theta(1+3d-2\beta F)^2}{144} - \frac{\theta\left[73-12\sqrt{37}-d\left(12-2\sqrt{37}+d\right)\right]}{16} \\ &= \frac{\theta\left[294\sqrt{37}-1762-4G+d\left(49\sqrt{37}-262-12d-4G\right)\right]}{392}\end{aligned}$$

which is positive if and only if $d < 0.28$. Comparing now $\widetilde{FPI}^B$ and $\widetilde{FPI}^{AO}$, we obtain that

$$\begin{aligned}\widetilde{FPI}^B - \widetilde{FPI}^{AO} &= \frac{\theta\left[73-12\sqrt{37}-d\left(12-2\sqrt{37}+d\right)\right]}{16} - \frac{(73{-}12\sqrt{37})\theta}{16} \\ &= \frac{\theta d\left(12-2\sqrt{37}+d\right)}{16}\end{aligned}$$

which is weakly positive if and only if $d > 2(\sqrt{37}-6) \simeq 0.17$, implying that $\widetilde{FPI}^B \geq \widetilde{FPI}^{AO}$; and becomes zero when $d = 0$, implying that $\widetilde{FPI}^B = \widetilde{FPI}^{AO}$ as in Corollary 2. Finally, comparing

$\widetilde{FPI}^R$ and FPI^R, we obtain

$$\begin{aligned}\widetilde{FPI}^R - FPI^R &= \frac{\theta(1+3d-2\beta F)^2}{144} - \frac{((4\sqrt{37}-19)-12(\sqrt{37}-6))\theta}{784} \\ &= \frac{(9(8\sqrt{37}-53)+49(1+3d-2\beta F)^2)\theta}{7056}\end{aligned}$$

which is negative for all admissible values of d and $FPI^R > \widetilde{FPI}^R$. In contrast, $FPI^{AO} = \widetilde{FPI}^{AO}$ and $\widetilde{FPI}^B = FPI^B$, since

$$\begin{aligned}\widetilde{FPI}^B - FPI^B &= \frac{\theta\left[73-12\sqrt{37}-d\left(12-2\sqrt{37}+d\right)\right]}{16} - \frac{\theta(73-12\sqrt{37})}{16} \\ &= \frac{\theta d\left(12-2\sqrt{37}+d\right)}{16}\end{aligned}$$

which is weakly positive if and only if $d > 2(\sqrt{37}-6) \simeq 0.17$, implying that $\widetilde{FPI}^B \geq FPI^B$; and becomes zero when $d=0$, implying that $\widetilde{FPI}^B = FPI^B$ as in the main model.

9.13 *Proof of Corollary 5*

Comparing $\widetilde{SPI}^R$ and $\widetilde{SPI}^B$, we obtain that

$$\begin{aligned}\widetilde{SPI}^R - \widetilde{SPI}^B &= \left[\frac{\theta(1372(1-d)(5+d(2+d)+8g)+32(G+3d-11)(24+\sqrt{37}+49g))}{43904}\right] \\ &\quad - \left[\frac{\theta\left\{925-152\sqrt{37}+8\left[\sqrt{37}-6g+d\left(141-24\sqrt{37}-d(1+d)-8g\right)\right]\right\}}{32}\right]\end{aligned}$$

which is positive for all admissible parameter values, entailing that $\widetilde{SPI}^R > \widetilde{SPI}^B$. Comparing now $\widetilde{SPI}^B$ and $\widetilde{SPI}^{AO}$, we find that

$$\begin{aligned}\widetilde{SPI}^B - \widetilde{SPI}^{AO} &= \left[\frac{\theta\left\{925-152\sqrt{37}+8\left[\sqrt{37}-6g+d\left(141-24\sqrt{37}-d(1+d)-8g\right)\right]\right\}}{32}\right] \\ &\quad - \left[\frac{\theta(925-152\sqrt{37}+8g(\sqrt{37}-6))}{32}\right] \\ &= \frac{\theta d\left[141-24\sqrt{37}-d(1+d)-8g\right]}{32}\end{aligned}$$

which is weakly negative for all admissible parameter values and, thus, $\widetilde{SPI}^{AO} \geq \widetilde{SPI}^B$; and is zero if $d=0$ implying that $\widetilde{SPI}^{AO} = \widetilde{SPI}^B$ as in the main model of Corollary 2. Comparing now $\widetilde{SPI}^R$ and $\widetilde{SPI}^{AO}$, we find that

$$\widetilde{SPI}^R - \widetilde{SPI}^{AO} = \left[\frac{\theta(1372(1-d)(5+d(2+d)+8g)+32(G+3d-11)(24+\sqrt{37}+49g))}{43904}\right] - \left[\frac{\theta(925-152\sqrt{37}+8g(\sqrt{37}-6))}{32}\right]$$

$$= \frac{\theta(1372(1-d)(5+d(2+d)+8g)+32(G+3d-11)(24+\sqrt{37}+49g) - 1372(925-152\sqrt{37}+8g(\sqrt{37}-6)))}{43904}$$

which is positive if and only if $d < \widehat{d}$, where cutoff $\widehat{d}$ solves

$$g = \frac{d\left[24\sqrt{37}-453-343d(1+d)+8\left(6506\sqrt{37}-39709+G\left(24+\sqrt{37}\right)\right)\right]}{392\left(7\sqrt{37}-38+4d-G\right)}.$$

Comparing $\widetilde{SPI}^R$ and SPI^R, we obtain

$$\widetilde{SPI}^R - SPI^R = \left[\frac{\theta(1372(1-d)(5+d(2+d)+8g)+32(G+3d-11)(24+\sqrt{37}+49g))}{43904}\right] - \left[\frac{\theta(2744(8g+5)-32(\sqrt{37}-11)(18-2\sqrt{37}-(66+98g)))}{87808}\right]$$

$$= \frac{\theta(343(1-d)(5+d(2+d)+8g)-343(5+8g)-8(\sqrt{37}-11)(24+\sqrt{37}+49g) + 8(3d+G-11)(24+\sqrt{37}+49g))}{10976}$$

which is negative for all admissible parameter values and, thus, $SPI^R > \widetilde{SPI}^R$. In addition, $SPI^{AO} = \widetilde{SPI}^{AO}$ and $\widetilde{SPI}^B < SPI^B$, since

$$\widetilde{SPI}^B - SPI^B = \left[\frac{\theta\left\{925-152\sqrt{37}+8\left[\sqrt{37}-6g+d\left(141-24\sqrt{37}-d(1+d)-8g\right)\right]\right\}}{32}\right] - \left[\frac{\theta(925-152\sqrt{37}+8g(\sqrt{37}-6))}{32}\right]$$

which is positive if and only if $d < \widetilde{d}$, where cutoff $\widetilde{d}$ solves

$$g = \frac{304\sqrt{37}-1850+d\left(24\sqrt{37}-141+d(1+d)\right)}{8\left(2\sqrt{37}-12-d\right)}.$$

When $d = 0$, this condition holds, entailing that $\widetilde{SPI}^B = SPI^B$.

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