Don't Leave the Regulator Alone in the Commons:

How Fishing Cooperatives Can Help Ameliorate Inefficiencies

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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 the policies of both 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 eliminated when the two agencies coexist. We then extend our model to a setting where regulator and artisanal organization have misaligned preferences, demonstrating that both agencies are still preferrable when the stock regenerates rapidly, but a single agency is preferrable otherwise.

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

JEL classification: H23, L13, Q5.

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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. Overall, we show that both agencies simultaneously managing the resource gives rise to zero (or small) inefficiencies under large parameter conditions. However, when these agencies have misaligned preferences, as we describe below, and the common pool resource regenerates slowly —such as most mollusks, the Pacific ocean perch, and the Sablefish— the presence of a single agency is socially preferable.

Our model considers a common pool resource (CPR) that can partially regenerate across periods and two firms exploiting it in each period. We study the effect of having a regulator alone (denoted as R), setting the aggregate allowable quota and fines; an artisanal organization alone, such as cooperatives and TURF programs, setting individual quotas and fines to each fisherman (which we denote as AO); or both regulatory agencies being simultaneously active (B).

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 R, AO, and B. 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 the regulatory agency (R or AO) sets quotas that are not stringent enough in the first period, but too stringent in the second 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 the R or AO cannot revise their quotas/fines across periods in an inflexible regime. 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 (B), however, we show that regulatory inefficiencies are eliminated 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 (R or AO), the R generates more inefficiencies than the AO does. Overall, our results suggest that, when agencies exhibit similar objective functions, the AO's presence is unambiguously welfare improving, giving rise to smaller inefficiencies when operating alone, or helping eliminate 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 as 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 (R or AO, but not both) should manage the resource, choosing the agency with the lowest administrative costs.

As an extension, we then examine scenarios where agencies have misaligned preferences, which can arise when the R considers the biodiversity loss of aggregate appropriation while the AO does not.[1] This modeling strategy allows us to study how the above regulatory inefficiencies is affected by the preference misalignment between R and AO. We show that, in this context, all agencies produce inefficiencies, including B. In particular, we identify that the AO (R) induces the overexploitation of the resource when it regenerates rapidly (slowly, respectively), as in the case of the pelagics such as Bigeye scad, Pacific herring or Sockeye salmon (mollusks, the Pacific ocean perch, or the Sablefish, respectively), whereas the B underexploits it.[2] This finding entails that, when agencies have asymmetric objectives, society faces a trade-off: either allow the resource to be overexploited given the management of only one agency (AO when the commons regenerates rapidly, R otherwise), or allow for it to be underexploited when both agencies simultaneously manage the resource. We then rank these inefficiencies, showing that the inefficiency from underexploiting the CPR is smaller than that from overexploiting it when the stock regenerates slowly, implying that B is socially preferrable in this context. In contrast, when the stock regenerates rapidly, the inefficiency from overexploitation under AO or R is smaller, making these agencies socially preferrable.

Table I summarizes our above results, reporting the agency (R, AO, or B) that gives rise to the smallest inefficiencies. Under a flexible policy regime (second column), no inefficiencies arise when R and AO have symmetric objective functions, which holds under every agency, as they

[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).

can all induce fisherman to appropriation socially optimal levels. When they have asymmetric objectives, however, the AO generates inefficiencies, as this agency ignores environmental damages, thus inducing an overexploitation of the resource. The R considers this environmental damage, and B takes into it account too, recommending a lower appropriation.

	Flexible regime	*Inflexible regime*	
	Any regeneration	Rapid regeneration	Slow regeneration
Symmetric objectives	No inefficiencies	B	B
Asymmetric objectives	R or B	B	R or AO

Table I. Agency generating the smallest inefficiency.

Under an inflexible regime (summarized in third and fourth columns), these results are affected. Specifically, when agencies have similar objectives (top row), the presence of both agencies (B) helps eliminate regulatory inefficiencies regardless of the regeneration rate of the resource, making this agency preferrable. In addition, if a single agency must manage the resource, our results show that the AO is superior to the R, entailing that the R should never be alone. When agencies are asymmetric in their objectives (bottom row), our finding suggest that the B remains superior only when the stock regenerates relatively rapidly. Otherwise, a single agency (R or AO) becomes socially preferrable.

Related literature. Since Hardin (1968), several studies have studied socially excessive exploitation 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 Cancino et al. (2007), Arnason (2009), Zhou and Segerson (2016), and Isaksen and Richter (2019). 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

[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).

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.

Other connected papers include 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 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. 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

$$c^1(e_i, e_j, \theta) = \frac{e_i(e_i + e_j)}{2\theta}$$

where $j \neq i$, which is symmetric across fisherman. Therefore, the marginal extraction cost is $\frac{2e_i+e_j}{2\theta}$, which is increasing in fisherman i's own effort, e_i, in its rival's effort, 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,

$$\pi_i^{1,AO} = e_i - \frac{e_i(e_i + e_j)}{2\theta} - \alpha \left[f_i \left(e_i - \bar{e}_i \right) - f_j \left(e_j - \bar{e}_j \right) \right]$$

and

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

where α (β) denotes the probability that fisherman i is monitored by the AO (R, respectively). 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.[4]

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

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

where superscript B denotes both regulatory agencies.

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

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

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 available again at the beginning of the second period. Hence, second-period profits when facing the AO (R) are

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

and

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

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

[4] 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.

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

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

To study the role of the AO and the R on fishermen's extractions, 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 agents (AO and R).

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

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

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*

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

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

As expected, second-period extraction 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-period equilibrium appropriation is*

$$e_i^{NR} = \frac{2\theta(9-2\delta)}{27}$$

which is positive under all parameter values, and second-period equilibrium appropriation is

$$x_i^{NR} = \frac{2\theta(8\delta+27g-9)}{81}$$

which is positive if and only if $g > \frac{9-8\delta}{27}$.

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.[5]

4 Flexible policy

In this section, we study how our above 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 in at the beginning of the first period and which stays in place throughout all subsequent periods. Hence, the time structure of the game under a flexible policy regime is:

1. In the first stage:

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

   (b) If only the R is present, it 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, $\bar{e}_i$ and $\bar{e}_j$, and first-period fines, f_i and f_j.[6]

   (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.

[5] The intial condition on g, $g < \frac{E}{\theta}$, holds in this setting if $g < \frac{4(9-2\delta)}{27}$. This condition is compatible with $g > \frac{9-8\delta}{27}$ since $\frac{4(9-2\delta)}{27} > \frac{9-8\delta}{27}$ holds for all values of δ.

[6] 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.

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

   (a) If only the AO is present, it 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 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.

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. 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 generality, section 7 considers an alternative setting, where the R exhibits a different objective function than the AO, assigning a weight to the biodiversity loss arising from the exploitation of the resource, i.e., environmental damage.) 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*

$$e_i^k = \frac{\theta(2-\delta)}{4} \quad \text{and} \quad x_i^k = \frac{\theta(2g+\delta)}{4}$$

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) $f_i^{AO} = \frac{2+\delta}{8\alpha}$ *and* $t_i^{AO} = \frac{1}{4\alpha}$ *under AO;*

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

c) $f_i^B = \frac{2+\delta}{8\alpha}$, $F^B = 0$, $t_i^B = \frac{1}{4\alpha}$ *and* $T^B = 0$ *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 the 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.

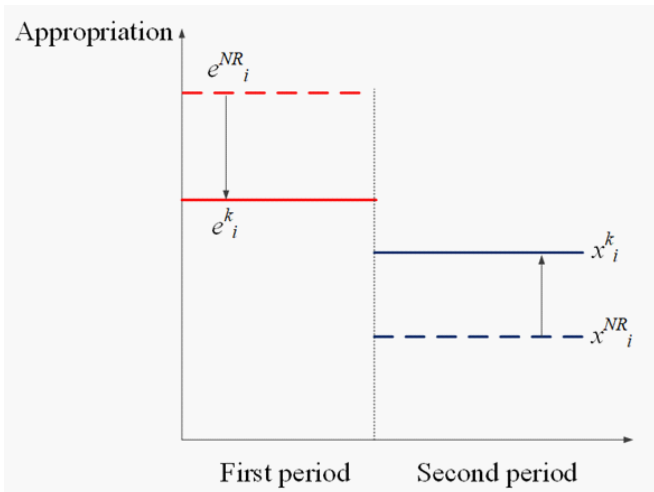

Figure 1. First- and second-period appropriation under a flexible policy regime.

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, but increasing 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.[7]

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

[7] 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.

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*

$$e_i^{AO} = \frac{\theta(9+\delta-3A)}{2\delta} \quad \textit{and} \quad x_i^{AO} = \frac{\theta\left(3+\delta-A\right)\left(\delta g-9+3A\right)}{2\delta^2}$$

and the fine is $f_i^{AO} = \frac{(\delta-9)+3\gamma}{4\alpha\delta}$, *where* $A \equiv \left(9+\delta^2\right)^{1/2}$.

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.[8] In addition, second-period appropriation increases in the stock abundance, θ, and growth rate of the initial stock, 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*

$$\begin{aligned} e_i^R &= \frac{\theta\left[3\left(3-C\right)+\delta\left(37-10\delta-2C\right)\right]}{98\delta} \quad \textit{and} \\ x_i^R &= \frac{\theta\left[5\delta+3-C\right]\left[(3-2\delta)C+\delta(12+49g+10\delta)-9\right]}{686\delta^2} \end{aligned}$$

and the fine is $F^R = \frac{(13\delta-9)+3C}{14\beta\delta}$, *where* $C \equiv \left[9+\delta(25\delta-12)\right]^{1/2}$.

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*

$$\begin{aligned} e_i^B &= \frac{\theta\left[1-\sqrt{D}+2\delta\left(12\delta-2\sqrt{D}+1\right)\right]}{8\delta} \quad \textit{and} \\ x_i^B &= \frac{\theta\left(1+6\delta-\sqrt{D}-1\right)\left(\sqrt{D}+2\delta\left(-12\delta+2\sqrt{D}+2g+1\right)-1\right)}{16\delta^2} \end{aligned}$$

and fines are $f_i^B = \frac{2-14\delta+3\sqrt{D}}{8\alpha\delta}$ *and* $F^B = \frac{4-\frac{5}{\delta}}{4\beta}$, *where* $D \equiv (6\delta-1)^2$.

Therefore, 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 thus makes the role of the R unnecessary.

[8] In particular, when $\delta \to 0$, fine f_i^{AO} approaches $\frac{1}{4\alpha}$ while when $\delta \to 1$ this fine approaches $\frac{3\sqrt{10}-8}{4\alpha}$.

6 Regulatory inefficiencies

In this section, we measure the difference in the 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. 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* $k = \{AO, R\}$*. When both regulators are present, no inefficiencies arise in equilibrium.*

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, which yields to 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, however, corollary 1 shows that $e_i^{B,IN} = e_i^{k,F}$ and $x_i^{B,IN} = x_i^{B,F}$ holds, thus giving rise to no inefficiencies in either period. In other words, the presence of both agencies helps correct the inefficiencies that one agency would not have been able to correct on its own.

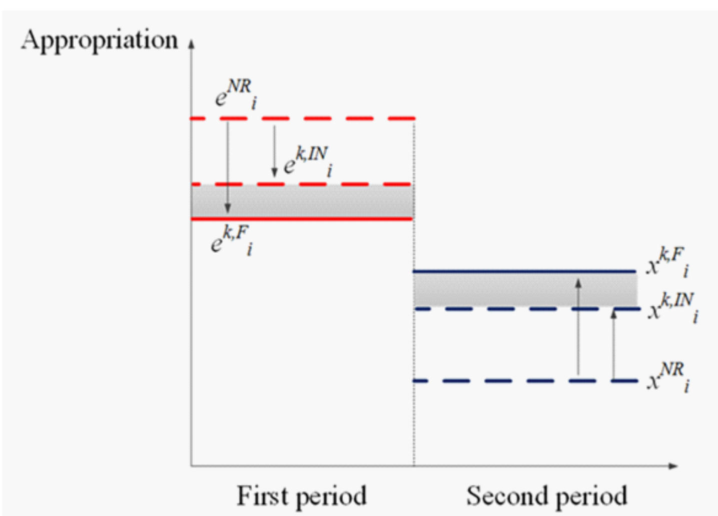

Figure 2. First- and second-period appropriation under an inflexible policy regime.

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

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

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, this result suggests that, while one regulatory agency alone (R or AO) give rise to inefficiencies in both periods, both agencies together eliminate the inefficiencies arising from operating under an inflexible policy regime (as shown in Corollary 1). In addition, we find that R produces more inefficiencies than the AO. Intuitively, this larger inefficiency 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 increasing second-period appropriation less significantly than the AO does, giving rise to the largest second-period inefficiencies as well.

In addition, FPI^k is unaffected by the regeneration rate, g, for every regulatory agency k. However, SPI^k is increasing in g since appropriation under a flexible regime, $x_i^{k,F}$, increases more significantly in g than appropriation under an inflexible regime, $x_i^{k,IN}$, does. Therefore, the inefficiencies from an inflexible regime remain unchanged in the first period as the resource regenerates faster, but are emphasized in the second period. In terms of policy recommendations, this result entails that R should not manage the resource when it regenerates fast (such as anchovies and Yellowtail flounder, although its regulatory inefficiencies are less substantial when the CPR regenerates slowly (such as mollusks or American plaice).

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 generality, this section allows agents to discount future payoffs, but assumes that such discounting is not extremely low, i.e., $\delta > 1/6$.

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. *When the R is present under a flexible policy (with or without AO), first- and second-period equilibrium appropriation levels are decreasing in d, while the fine is increasing in d if and only if $d < \frac{1+2\delta}{5\delta}$.*

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, these appropriation levels are lower, while fines increase (although this occurs only when d is not too high), indicating that the R seeks more conservation as the environmental damage from appropriation increases, which holds when the AO is also present and otherwise.

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 and second -period equilibrium appropriation levels are constant 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 agents are present, appropriation levels are unaffected by environmental damage. Intuitively, the R seeks to reduce appropriation as d increases whereas the AO responds increasing quotas to fishermen to compensate for the profit decrease (since the AO ignores environmental damage in its objective function), ultimately yielding no change in equilibrium appropriation levels when both agents are present.

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).[9] 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

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

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 ($d > 0$).

The following corollary examines these two forms of efficiency where, as in section 6, 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 $\tilde{x}_i^{k,IN} < \tilde{x}_i^{k,F}$ for $k = \{R, AO\}$ but $\tilde{x}_i^{B,IN} > \tilde{x}_i^{B,F}$, under all parameter values. 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

[9] 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 of that regulatory setting k (or, for that matter, on any other setting $k' \neq k$).

inefficiency for the AO; although this inefficiency is nil for the R and B.

In the second period, however, the R and AO underexploit the resource, entailing $\tilde{x}_i^{R,IN} < \tilde{x}_i^{R,F}$ and $\tilde{x}_i^{AO,IN} < \tilde{x}_i^{AO,F}$, 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 regulator is present, as he 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 $\widetilde{FPI}$ to differentiate them from first-period inefficiencies in our main model (see Corollary 1).

Corollary 4. *First-period inefficiencies satisfy* $\widetilde{FPI}^R \geq \widetilde{FPI}^{AO} \geq \widetilde{FPI}^B \geq 0$ *when* $d < \hat{d}$, $\widetilde{FPI}^R \geq \widetilde{FPI}^B \geq \widetilde{FPI}^{AO} \geq 0$ *when* $\hat{d} \leq d < \bar{d}$, $\widetilde{FPI}^B \geq \widetilde{FPI}^R \geq \widetilde{FPI}^{AO} \geq 0$ *when* $\bar{d} \leq d < \breve{d}$, *and* $\widetilde{FPI}^B \geq \widetilde{FPI}^{AO} \geq \widetilde{FPI}^R \geq 0$ *otherwise; where cutoffs are* $\breve{d} = 11 - 4\sqrt{10} + \sqrt{157 - 48\sqrt{10}} \approx 0.633$, $\overline{d} = \frac{\sqrt{13}-1}{8} \approx 0.3256$ *and* $\hat{d} = \sqrt{10} - 3 \approx 0,1622$*. Comparing these inefficiencies against those in Corollary 1 we obtain that* $\widetilde{FPI}^R < FPI^R$, $\widetilde{FPI}^{AO} = FPI^{AO}$, *and* $\widetilde{FPI}^B > FPI^B = 0$.

This ranking of inefficiencies illustrates that, when R and AO exhibit relatively aligned preferences (low values of d), we obtain the same ranking as in the base model, that is, $FPI^R \geq FPI^{AO} \geq FPI^B$, where R generates the largest inefficiencies. However, when their preferences become more misaligned (higher d), the R helps internalize the environmental externality, becoming the most efficient agency when d is sufficiently high. As a consequence, inefficiencies are smaller for the R when $d > 0$ than otherwise, that is, $\widetilde{FPI}^R < FPI^R$; and coincide for the AO. For B, which did not give rise to inefficiencies in the base model (where $d = 0$), generates inefficiencies when $d > 0$.

We next rank second-period inefficiencies in the three regulatory settings.

Corollary 5. *Second-period inefficiencies satisfy* $\widetilde{SPI}^R \geq \widetilde{SPI}^{AO} \geq 0 \geq \widetilde{SPI}^B$ *if* $d \leq d^*(g)$, *but* $\widetilde{SPI}^{AO} \geq \widetilde{SPI}^R \geq 0 \geq \widetilde{SPI}^B$ *otherwise. Comparing these inefficiencies against those in Corollary 2, we obtain that* $\widetilde{SPI}^R < SPI^R$, $\widetilde{SPI}^{AO} = SPI^{AO}$, *and* $\widetilde{SPI}^B < SPI^B = 0$. *For compactness, cutoff* $d^*(g)$ *is presented in the proof.*

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, and it should not manage the resource; but otherwise the AO is the agent giving rise to the most inefficiencies. The B, however, generates a negative inefficiency under all values of d, i.e., $\tilde{x}_i^{R,F} < \tilde{x}_i^{B,IN}$, implying that it overexploits the commons relative to its efficient level. As a consequence, choosing the regulatory setting (R, AO, or B) has a trade-off. In the first period, the R or B generally give rise to the lowest inefficiencies, but in the second period the decision depends on whether society prefers a positive inefficiency with R (underexploitation relative to the social optimum) or a negative inefficiency with B (overexploitation).

Figure 3 combines our results in corollaries 4 and 5, where cutoff $d^*(g)$ is approximately linear in the range of g depicted. Overall, when the preferences of R and AO are relatively aligned (low values of d), the B is the regulatory setting that generates the smallest inefficiencies in all periods, and should then be promoted to manage the CPR. When their preferences are relatively misaligned (intermediate values of d), the AO (B) yields the smallest inefficiency in the first (second) period, implying that the AO (B) should manage the CPR when society seeks to minimize first-period (second-period, respectively) inefficiencies. Finally, when preferences of R and AO are extremely different (high values of d, as when appropriation generates severe pollution), the R (B) generates the smallest inefficiencies in the first (second) period because the R's presence in both settings helps internalize the environmental externality that the AO ignores.

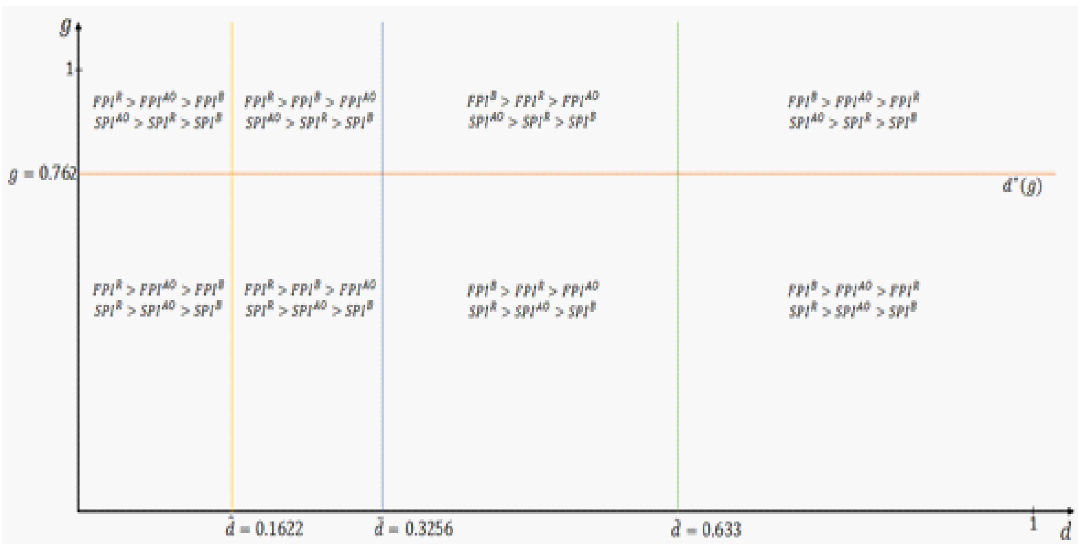

Figure 3. Ranking of FPIs and SPIs.

When first- and second-period inefficiencies have opposite signs, a natural question is which of them dominates, thus giving rise to an over- or an underexploitation of the resource across all periods. To measure this overall inefficiency, we measure the total inefficiency of regulatory setting k as follows

$$\begin{aligned} TI^k &= FPI^k + SPI^k \\ &= (e_i^{k,IN} - e_i^{k,F}) + (x_i^{k,F} - x_i^{k,IN}). \end{aligned}$$

for the base model, and similarly for the extension model, where $\widetilde{TI}^k = \widetilde{FPI}^k + \widetilde{SPI}^k$. When $d = 0$, total inefficiencies coincide, i.e., $TI^k = \widetilde{TI}^k$ for all k. The next corollary ranks total inefficiencies.

Corollary 6. *Total inefficiencies satisfy:*

1. *If* $d = 0$*, total inefficiencies satisfy* $TI^R > TI^{AO} > TI^B = 0$.
2. *If* $d > 0$*, total inefficiencies satisfy* $\widetilde{TI}^R > \widetilde{TI}^{AO} > 0 \geq \widetilde{TI}^B$ *if* $g > g^*(d)$*, but* $\widetilde{TI}^{AO} > \widetilde{TI}^R > 0 \geq \widetilde{TI}^B$ *otherwise. (Cutoff* $g^*(d)$ *is, for compactness, presented in the proof.)*
3. *Their absolute values satisfy* $\left|\widetilde{TI}^R\right| > \left|\widetilde{TI}^B\right|$ *if and only if* $g < g_R$*, and* $\left|\widetilde{TI}^{AO}\right| > \left|\widetilde{TI}^B\right|$ *if and only if* $g < g_{AO}$*. (Cutoffs* g_R *and* g_{AO} *are, for compactness, presented in the proof.)*

When appropriation does not generate environmental damages, $d = 0$, the R is the regulatory setting producing the largest total inefficiencies while the combination of both R and AO (in B) eliminates all inefficiencies. When environmental damages are present, a similar ranking applies if the resource regenerates rapidly, $g > g^*(d)$, but we still face a trade-off: R and AO yield overexploitation ($TI^R, TI^{AO} > 0$) while B gives rise to underexploitation ($TI^B < 0$). Comparing their absolute values, however, point 3 of Corollary 6 finds that, while both R, AO, and B are all suboptimal, B is more desirable when the resource does not regenerate rapidly, but R or AO may be preferable otherwise.

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.

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-Symmetric agencies. Our results also help evaluate whether inefficiencies are larger when only one regulatory agency is present (AO or R) or both are (under B). As discussed above, under flexible policies no inefficiencies arise, which holds under AO, R, or B, implying that the presence of one or more regulatory agencies does not affect equilibrium outcomes or welfare. Under inflexible policies, however, inefficiencies emerge, but we show that they coincide across regulatory settings, that is, the difference between equilibrium and first-best appropriation coincides under AO, R, and B.

This is due to the fact that both R and AO face, essentially, similar objective functions, implying that they both seek to induce the same socially optimal appropriation levels in each period. Therefore, when both agencies are simultaneously active under B, the R anticipates the quotas and fines that the AO sets, making the role of the regulator unnecessary. Intuitively, this result can be interpreted as free-riding in a sequential context, where the R slacks, leaving all the responsibility to the AO in the subsequent period, as the R anticipates the AO inducing socially optimal appropriation levels.[10]

In summary, 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.

Overlapping regulations-Asymmetric agencies. Our above results are, however, affected when the AO and R exhibit different objective functions, 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. In addition, the presence of both regulatory agencies now yields different results than when only one agency is active. Specifically, the R anticipates the appropriation levels of the AO, but seeks a lower appropriation level, thus setting positive fines; as opposed to what happened when their preferences are symmetric where $F = 0$. As a consequence, the sequential free-riding incentives between R and AO are ameliorated as agencies' preferences become more asymmetric. As this asymmetry increases (severe environmental damage), the R's role becomes more necessary and sets more stringent fines.

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,

[10] For robustness, we confirm that the same equilibrium results arise when the order of R and AO is switched, so that AO acts first and the R responds with its own policy decision.

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. Specifically, the AO (R) produce an overexploitation of the resource when it regenerates rapidly (slowly, respectively), whereas B gives rise to an underexploitation of the resource under all parameter conditions. This result suggests that, under asymmetric regulatory agencies, society faces a trade-off: either allow the resource to be overexploited when it is managed by only one agency (AO when the commons regenerates rapidly, R otherwise), or allow for it to be underexploited when both agencies simultaneously manage the resource. We nonetheless rank the relative size of these inefficiencies, to identify which of them is the smallest (in absolute value). When the stock regenerates slowly, the underexploitation that the B entails is socially optimal, whereas when it regenerates rapidly, the AO or R is socially preferrable.

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.

9 Appendix

9.1 *Proof of Lemma 1*

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

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

Differentiating with respect to x_i, yields

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

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

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

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

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

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

9.2 *Proof of Proposition 1*

In the first period, without any form of 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 $x_i^{NR}(E) = x_j^{NR}(E) = \frac{2[\theta(1+g)-E]}{3}$, are

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

Therefore, every fisherman i solves

$$\max_{e_i \geq 0} \quad e_i - \frac{e_i(e_i + e_j)}{2\theta} + \delta \frac{\theta(1+g) - (e_i + e_j)}{9}$$

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

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

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

$$e_i^{NR} = \frac{2\theta(9-2\delta)}{27}.$$

which is positive if $\delta < \frac{9}{2}$, which holds because $\delta < 1$ by assumption. Therefore, second-period equilibrium appropriation is

$$x_i^{NR} = \frac{2\left[\theta(1+g) - (e_i^{NR} + e_j^{NR})\right]}{3} = \frac{2\theta(8\delta + 27g - 9)}{81},$$

which is positive if and only if $g > \frac{9-8\delta}{27}$.

9.3 *Proof or Proposition 2*

9.3.1 Only AO is present

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

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

Differentiating with respect to x_i, yields

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

Solving for x_i, we obtain a best response function

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

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

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

which exceeds that under any form of regulation 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 with and without the *AO*, 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.

$$\max_{\bar{e}_i,\bar{e}_j,f_i,f_j\geq 0} \quad \pi_o \quad = \quad \left[x_i - \frac{x_i\left(x_i+x_j\right)}{2\left[\theta(1+g)-E\right]} - \alpha\left[t_i\left(x_i-\bar{x}_i\right)-t_j\left(x_j-\bar{x}_j\right)\right]\right] + \left[x_j - \frac{x_j\left(x_i+x_j\right)}{2\left[\theta(1+g)-E\right]} - \alpha\left[t_j\left(x_j-\bar{x}_j\right)-t_i\left(x_i-\bar{x}_i\right)\right]\right].$$

Instead of finding the AO's quotas and fines directly, 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,

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

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

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

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

$$\frac{\theta(1+g)-E}{2} = \frac{2\left[1-\alpha\left(2t_i-t_j\right)\right]\left[\theta(1+g)-E\right]}{3}$$

which, solving for t_i, yields the fine that induces fisherman i to appropriate exactly x_i^{SO}, that is,

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

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

$$\frac{\theta\left(4-\delta-4\alpha f_i\right)-2(2e_i+e_j)}{4\theta}=0$$

Solving for e_i, we obtain a best response function

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

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.

$$e_i^{AO} = \frac{1}{6}\theta\left[4 - \delta - 4\alpha(2f_i + f_j)\right]$$

which are 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.

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

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

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

Differentiating with respect to e_i, yields

$$\frac{\theta(2-\delta) - 2e_i - 2e_j}{2\theta} = 0$$

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

$$e_i^{SO} = \frac{\theta(2-\delta)}{4}.$$

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

$$\frac{\theta(2-\delta)}{4} = \frac{1}{6}\theta\left[4 - \delta - 4\alpha(2f_i + f_j)\right]$$

which, solving for t_i, yields

$$f_i^{AO} = \frac{2+\delta}{8\alpha}.$$

which is positive for all parameter values. Inserting these results into $x_i^{AO}(E)$, yields a second-period equilibrium appropriation $x_i^{AO} = \frac{\theta(2g+\delta)}{4}$. 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

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

Differentiating with respect to x_i, yields

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

Solving for x_i, we obtain a best response function

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

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

$$x_i^R(E) = \frac{(2 - \beta T)\,[\theta(1+g) - E]}{3}$$

which exceeds second-period appropriation without regulation, $x_i^{NR}(E)$, if and only if $T < \frac{2}{\beta}$. 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.

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

where the last term in every square bracket denotes the equal share of the fine, $T/2$, that every fisherman pays if their aggregate appropriation, $x_i + x_j$, exceeds the aggregate quota, $\hat{x}$. The last term represents that the R returns the collected fines to society in the form of a lump sum subsidy (to guarantee that the fine is revenue neutral), which simplifies the above problem to:

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

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, 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

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

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,

$$\frac{(2 - \beta T)\left[\theta(1+g) - E\right]}{3} = \frac{\theta(1+g) - E}{2}$$

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

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

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

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

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

$$e_i^R = \frac{1}{6}\theta\left(4 - \delta - 2\beta F\right)$$

which is positive for all parameter values, increases in the abundance of the initial stock, θ, but decreases in fisherman i's expected penalty, βF.

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

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

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

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

Differentiating with respect to e_i and e_j and solving, yields

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

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

$$\widehat{e} = e_i^{SO} = \frac{\theta(2-\delta)}{4}.$$

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

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

which, solving for F, yields a fine

$$F^R = \frac{2+\delta}{4\beta}.$$

which is positive for all parameter values. Inserting this result into $x_i^{SO}(E) = \frac{\theta(1+g)-E}{2}$, we find that second-period equilibrium appropriation is

$$x_i^R = \frac{\theta(2g+\delta)}{4}$$

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

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

As in previous sections of this proof, 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 shows the penalty if aggregate extractions exceed the quota.

Differentiating with respect to x_i, we obtain

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

Solving for x_i, we obtain a best response function.

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

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

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

which increases in the available stock at the beginning of the second period, $\theta(1+g) - E$, and in his rival's penalty, t_j. However, second-period appropriation 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.

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

Differentiating with respect to x_i, yields

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

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

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

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 α values.

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

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

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

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

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

$$\widehat{x} = x_i^{SO} = \frac{\theta(1+g)-E}{2}.$$

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

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

or

$$T^B = 0$$

which is positive for all values of β. Therefore, the penalty from the AO 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

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

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

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

Solving for e_i, we obtain a best response function

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

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

$$e_i^B=\frac{\theta\left[4\left(1-\alpha(f_i-2f_j)\right)-2\beta F-\delta\right]}{6}.$$

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

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

As we showed in the previous section of this proof, the above maximization function can be rearranged as follows,

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

Differentiating with respect to e_i, yields

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

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

$$e_i^B(F)=\frac{\theta\left[2\left(1-\beta F\right)-\delta\right]}{4}.$$

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

$$\frac{\theta\left[4\left(1-\alpha(f_i-2f_j)\right)-2\beta F-\delta\right]}{6}=\frac{\theta\left[2\left(1-\beta F\right)-\delta\right]}{4}$$

Invoking symmetry in $f_i = f_j$, and solving for f_i, yields

$$f_i^B(F) = \frac{2(1+\beta F)+\delta}{8\alpha}$$

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 bot periods, as follows.

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

As in previous settings, we can alternatively solve this problem by first finding 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

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

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

$$e_i^B = \frac{\theta(2-\delta)}{4}.$$

Setting it equal to the equilibrium first-period appropriation found above, e_i^B, but evaluated at $f_i^B(F) = \frac{2(1+\beta F)+\delta}{8\alpha}$, that is, $e_i^B(F) = \frac{\theta[2(1-\beta F)-\delta]}{4}$, so that

$$\frac{\theta\left[2(1-\beta F)-\delta\right]}{4} = \frac{\theta(2-\delta)}{4}$$

Solving for F, yields $F^B = 0$, which entails that the fine from the AO in this period is $f_i^B = \frac{2+\delta}{8\alpha}$. Inserting these results into second-period appropriation, $x_i^B(E)$, we find that

$$x_i^B = \frac{\theta(\delta+2g)}{4}$$

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

$$\frac{\theta(2-\delta)}{4} > \frac{\theta(\delta+2g)}{4}$$

which simplifies to $g < 2-\delta$. This condition on g, however, is satisfied since the initial condition,

$g < \frac{E}{\theta}$, yields $g < \frac{2-\delta}{2}$ 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

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

Differentiating with respect to x_i, yields

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

Solving for x_i, we obtain a best response function

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

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

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

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

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

Differentiating with respect to e_i, yields

$$1 - \frac{2\delta}{9} - \frac{2e_i + e_j}{2\theta} - \frac{2\delta\alpha\left(4f_i - 5f_j\right)\left[\alpha\left(f_i + f_j\right) - 1\right]}{9} - \alpha f_i = 0$$

Solving for e_i, we obtain best response function

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

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.

$$e_i^* = \frac{2\theta\left[\alpha\left[2f_i\left(\alpha\delta f_j + 13\delta - 9\right) + f_j\left(9 + 28\delta\alpha f_j - 28\delta\right) - 26\alpha\delta f_i^2\right] + 9 - 2\delta\right]}{27}$$

which is positive if and only if $\alpha \notin (\underline{\alpha}_1, \overline{\alpha}_1)$, where cutoffs $\underline{\alpha}_1$ and $\overline{\alpha}_1$ are

$$\underline{\alpha}_1 \equiv \frac{2f_i(13\delta - 9) + f_j(9 - 28\delta) - J}{4\delta\left(13f_i - 14f_j\right)\left(f_i + f_j\right)} \quad \text{and}$$

$$\overline{\alpha}_1 \equiv \frac{2f_i(13\delta - 9) + f_j(9 - 28\delta) + J}{4\delta\left(13f_i - 14f_j\right)\left(f_i + f_j\right)}$$

where $J \equiv 3\left[4\left(9 + 13\delta^2\right)f_i^2 - 4(3 - 8\delta)(3 - 5\delta)f_i f_j + (3(3 - 56\delta) + 112\delta^2)f_j^2\right]^{1/2}$.

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

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

which simplifies to

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

As in previous settings, we find socially optimal appropriation levels in the above program, and then the corresponding fines. Differentiating with respect to e_i, yields

$$\frac{\theta\left[9 - 4\delta + 2\alpha\delta\left(f_i + f_j\right)\left(\alpha\left(f_i + f_j\right) - 1\right)\right] - 9e_i - 9e_j}{9\theta} = 0$$

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

$$e_i^{SO} = \frac{\theta\left[9 - 4\delta + 2\delta\alpha\left(f_i + f_j\right)\left(\alpha\left(f_i + f_j\right) - 1\right)\right]}{18}.$$

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

$$f_i^{AO} = \frac{(\delta - 9) + 3\gamma}{4\alpha\delta}$$

where $A \equiv (9 + \delta^2)^{1/2}$. Fine 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

$$e_i^{AO} = \frac{\theta(9+\delta-3A)}{2\delta}$$

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

$$x_i^{AO} = \frac{\theta\,(3+\delta-A)\,(\delta g-9+3A)}{2\delta^2}.$$

9.5 ***Proof of Lemma 3***

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

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

Differentiating with respect to x_i, yields

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

Solving for x_i, we obtain a best response function

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

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

$$x_i^R(E) = \frac{(2-\beta F)[(1+g)\theta-E]}{3}$$

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

Second stage. Fisherman i anticipates equilibrium second-profits appropriations, $x_i^R(E)$ 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

$$\frac{\theta(2-\beta F)(9+4\beta\delta F-2\delta)-9(2e_i+e_j)}{18\theta} = 0$$

Solving for e_i, we obtain a best response function

$$e_i(e_j) = \begin{cases} \frac{\theta}{18}(2-\beta F)(9+4\delta\beta F-2\delta) - \frac{1}{2}e_j, \text{ if } e_j < \frac{\theta}{9}(2-\beta F)(9+4\delta\beta F-2\delta) \\ 0 \ \text{ otherwise.} \end{cases}$$

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

$$e_i^R = \frac{\theta}{27}(2-\beta F)(9+4\delta\beta F-2\delta)$$

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

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

As in the proof of Proposition 2, the R finds the first-period socially optimal aggregate 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

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

Differentiating with respect to e_i and e_j and solving, yields

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

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

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

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

$$\frac{\theta}{9}[9+2\delta(\beta F-2)(\beta F+1)] = \frac{2\theta}{27}(2-\beta F)(9+4\delta\beta F-2\delta)$$

which, solving for fine F, yields

$$F^R = \frac{3C + (13\delta - 9)}{14\delta\beta}.$$

where $C \equiv [\delta(25\delta - 12) + 9]^{1/2}$, which is positive for all β and δ values greater than zero. Inserting this result into $x_i^{SO}(E)$, we find that second-period equilibrium appropriation is

$$x_i = \frac{(5\delta - C + 3)\,\theta\,[3C - 9 + \delta\,(10\delta - 2C + 49g + 12)]}{686\delta^2}.$$

The second-period equilibrium appropriation increases in the initial stock, θ.

Evaluating second-period equilibrium appropriation at penalty F^*, yields

$$e_i^R = \frac{\theta\,[3\,(3 - C) + \delta\,(37 - 10\delta - 2C)]}{98\delta},$$

Similarly, evaluating first-period equilibrium appropriation at penalty F^*, yields

$$x_i^R = \frac{\theta\,[5\delta + 3 - C]\,[(3 - 2\delta)C + \delta(12 + 49g + 10\delta) - 9]}{686\delta^2}.$$

9.6 *Proof of Lemma 4*

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

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

Differentiating with respect to e_i, we obtain

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

Solving for x_i, we obtain a best response function

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

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

$$x_i(f_i, f_j, F) = \frac{[\theta(1+g) - E]\,[2 - \beta F - 2\alpha(2f_i - f_j)]}{3}$$

which increases in the available stock at the beginning of the second period, $\theta(1+g) - E$, and in his rival's penalty, t_j. However, second-period appropriation decreases in fisherman i's penalty, t_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

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

Differentiating with respect to x_i, yields

$$\frac{(2-\beta F)\left[9+\delta\left(4\beta F-2\right)\right]\theta - 9\left(2e_i+e_j\right) + 2\alpha\theta\left[f_i\left(9-8\delta-2\alpha\delta f_j+\beta\delta F\right)+\delta f_j\left(10\left(1-\alpha f_j\right)+\beta F\right)+8\alpha\delta f_i^2\right]}{18\theta} =$$

Solving for e_i, we obtain a best response function

$$e_i(e_j) = \begin{cases} \frac{\theta(2-\beta F)(9-2\delta+4\delta\beta F)-2\alpha\theta\left(f_i(9-8\delta-2\delta\alpha f_j+\delta\beta F)+\delta f_j(\beta F-10\alpha f_j+10)+8\delta\alpha f_i^2\right)}{18} - \frac{e_j}{2}, \\ \text{if } e_j < \frac{\theta(2-\beta F)(9-2\delta+4\delta\beta F)-2\alpha\theta\left(f_i(9-8\delta-2\delta\alpha f_j+\delta\beta F)+\delta f_j(\beta F-10\alpha f_j+10)+8\delta\alpha f_i^2\right)}{9} \\ 0 \quad \text{otherwise.} \end{cases}$$

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

$$e_i^B = \frac{\theta\left[2\alpha\left(28\alpha\delta f_j^2 - f_i\left[26\delta\left(\alpha f_i-1\right)+\delta\beta F\right]+18+f_j\left[2\alpha\delta f_i-\delta\left(\beta F+28\right)+9\right]\right)-\left(\beta F-2\right)\left(\delta\left(4\beta F-2\right)+9\right)\right]}{27}$$

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

$$\underline{\alpha}_2 = \frac{2(9-13\delta)f_i + (28\delta-9)f_j - \delta\beta F\left(f_i+f_j\right) - H}{4\delta\left(14f_j-13f_i\right)\left(f_i+f_j\right)} \quad \text{and}$$

$$\overline{\alpha}_2 = \frac{2(9-13\delta)f_i + (28\delta-9)f_j - \delta\beta F\left(f_i+f_j\right) + H}{4\delta\left(14f_j-13f_i\right)\left(f_i+f_j\right)}$$

where

$$H \equiv \left[\left[f_i\left(18+\delta\left(\beta F-26\right)\right)+f_j\left(\delta\left(\beta F+28\right)-9\right)\right]^2 + 4\delta\left(f_i+f_j\right)\left(13f_i-14f_j\right)\left(2-\beta F\right)\left(9-2\delta\left(1-2\beta F\right)\right)\right]^{1/2}$$

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

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

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

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

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

$$f_i^B = \frac{\delta - 9 - 8\delta\beta F + 3\sqrt{9+12\delta\beta F+(\delta+2\delta\beta F)^2}}{4\delta\alpha}.$$

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

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

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

As in previous settings, we can alternatively solve this problem by first finding 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

$$\frac{\delta+2\beta\delta F\left(\delta+2\beta\delta F-\sqrt{(\delta+2\beta\delta F)^2+12\beta\delta F+9}+6\right)-3\sqrt{(\delta+2\beta\delta F)^2+12\beta\delta F+9}+9}{\delta} - \frac{e_i+e_j}{\theta} = 0$$

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

$$e_i^B = \frac{\theta\left(\delta+2\beta\delta F\left(\delta+2\beta\delta F-\sqrt{(\delta+2\beta\delta F)^2+12\beta\delta F+9}+6\right)-3\sqrt{(\delta+2\beta\delta F)^2+12\beta\delta F+9}+9\right)}{2\delta}.$$

Setting it equal to the equilibrium first-period appropriation found in the second stage, e_i^B, but evaluated at $f_i^B(F) = \frac{\delta-9-8\delta\beta F+3\sqrt{9+12\delta\beta F+(\delta+2\delta\beta F)^2}}{4\delta\alpha}$ and solving for F, yields a continuum of solutions for F^B, such as $F^B = 0$. Then, evaluating the above results at $F = \frac{4-\frac{5}{\delta}}{4\beta}$, we find that

$$f_i^B = \frac{2-14\delta+3\sqrt{D}}{8\alpha\delta},$$

$$e_i^B = \frac{\theta\left(1-\sqrt{D}+2\delta\left(12\delta-2\sqrt{D}+1\right)\right)}{8\delta}, \text{ and}$$

$$x_i^B = \frac{\theta\left(1+6\delta-\sqrt{D}\right)\left[\sqrt{D}+2\delta\left(-12\delta+2\sqrt{D}+2g+1\right)-1\right]}{16\delta^2}.$$

where $D \equiv (6\delta - 1)^2$.

9.7 *Proof of Corollary 1*

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

$$\begin{aligned} e_i^{AO,IN} - e_i^{AO,F} &= \left(5 - 3\sqrt{\frac{5}{2}}\right)\theta - \frac{\theta}{4} \\ &= \frac{1}{4}\left(19 - 6\sqrt{10}\right)\theta \end{aligned}$$

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

$$\begin{aligned} e_i^{R,IN} - e_i^{R,F} &= \frac{1}{98}\left(36 - \sqrt{22}\right)\theta - \frac{\theta}{4} \\ &= \frac{1}{196}\left(23 - 2\sqrt{22}\right)\theta \end{aligned}$$

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

Finally, when both AO and R are present, we obtain

$$e_i^{B,IN} - e_i^{B,F} = \left(\frac{1}{4}\theta\right) - \left(\frac{1}{4}\theta\right) = 0$$

Therefore, $e_i^{B,IN}$ is equal to $e_i^{B,F}$.

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

$$\begin{aligned} x_i^{AO,F} - x_i^{AO,IN} &= \left[\frac{1}{4}(2g+1)\theta\right] - \left[\frac{1}{2}\left(4 - \sqrt{10}\right)\left(g + 3\sqrt{10} - 9\right)\theta\right] \\ &= \frac{1}{4}\left[2\left(\sqrt{10} - 3\right)g - 42\sqrt{10} + 133\right]\theta \end{aligned}$$

which is positive for all $g > 0$ and $\theta > 0$. Therefore, $x_i^{AO,F}$ is greater than $x_i^{AO,IN}$.

When only the R is present, we find that

$$\begin{aligned} x_i^{R,F} - x_i^{R,IN} &= \left[\frac{1}{4}(2g+1)\theta\right] - \left[\frac{1}{686}\left(8 - \sqrt{22}\right)\left(49g + \sqrt{22} + 13\right)\theta\right] \\ &= \frac{\left[98\left(\sqrt{22} - 1\right)g + 10\sqrt{22} + 179\right]\theta}{1372} \end{aligned}$$

which is positive for all $\theta > 0$ and $g > 0$. This implies that $x_i^{R,F}$ is greater than $x_i^{R,IN}$.

When both AO and R are present, we obtain

$$x_i^{B,F} - x_i^{B,IN} = \left[\frac{1}{4}(2g+1)\theta\right] - \left[\frac{1}{4}(2g+1)\theta\right] = 0$$

Therefore, $x_i^{B,IN}$ is equal to $x_i^{B,F}$.

9.8 *Proof of Corollary 2*

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

$$\begin{aligned} FPI^R - FPI^{AO} &= \left[\frac{\left(98\left(\sqrt{22}-1\right)g + 10\sqrt{22} + 179\right)\theta}{1372}\right] - \left[\frac{1}{4}\left(2\left(\sqrt{10}-3\right)g - 42\sqrt{10} + 133\right)\theta\right] \\ &= \frac{1}{98}\left(147\sqrt{10} - \sqrt{22} - 454\right)\theta \approx 0.0629902\theta \end{aligned}$$

which is positive for all θ admissible parameter values. Therefore, the FPI is larger with R than with AO. Furthermore, since first-period inefficiency with AO and R is zero, FPI^B, and FPI^{AO} and FPI^R are positive for all allowable parameter values, we know that $FPI^k > FPI^B$ for $k \in \{AO, R\}$.

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

$$\begin{aligned} SPI^R - SPI^{AO} &= \left[\frac{98\left(\sqrt{22}-1\right)g + 10\sqrt{22} + 179}{1372}\right] - \left[\frac{1}{4}\left(2\left(\sqrt{10}-3\right)g - 42\sqrt{10} + 133\right)\theta\right] \\ &= \frac{98g\left(\sqrt{22} - 7\left(\sqrt{10}-3\right)\theta - 1\right) + 2401\left(6\sqrt{10} - 19\right)\theta + 10\sqrt{22} + 179}{1372} \end{aligned}$$

which is positive for all g and θ admissible parameter values. Therefore, the SPI is larger with R than with AO. In addition, since second-period inefficiency with AO and R is zero, SPI^B, and SPI^AO and SPI^R are positive for all allowable parameter values, we know that $SPI^k > SPI^B$ for $k \in \{AO, R\}$.

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.

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

Differentiating with respect to x_i, yields

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

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

$$\tilde{x}_i^R(E) = \frac{(1-d)\left[\theta(1+g)-E\right]}{2}.$$

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

$$\frac{\theta\left[3d\delta(1-d)-\beta F+2\right]-2e_i-e_j}{2\theta} = 0$$

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

$$e_i(e_j) = \begin{cases} \frac{\theta[3d\delta(1-d)-\beta F+2]}{2} - \frac{1}{2}e_j, & \text{if } e_j < \theta\left[3d\delta(1-d)-\beta F+2\right], \\ 0 \ \ \text{otherwise.} \end{cases}$$

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

$$\tilde{e}_i^* = \frac{\theta[3d\delta(1-d)-\beta F+2]}{3}$$

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

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

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

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

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

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

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

$$F^* = \frac{3d\left[(4-5d)\delta+2\right]+3\delta+2}{4\beta}.$$

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

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

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

$$\tilde{e}_i = \frac{\theta(2-\delta)}{4}, \quad \tilde{x}_i = \frac{\theta(\delta+2g)}{4} \quad \text{and} \quad F = \frac{3\delta+2}{4\beta I}$$

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.

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

Differentiating with respect to x_i, yields

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

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

$$\tilde{x}_i^B = \frac{\left[\theta(1+g)-E\right](1-\beta T)}{2}.$$

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.

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

Differentiating with respect to x_i, yields

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

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

$$\tilde{x}_i^{B,F} = \frac{(1-d)\,[\theta(1+g) - E]}{2}.$$

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

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

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

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

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

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

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.

$$\tilde{e}_i^* = \frac{\theta\left[4 - \delta(1-d^2) - 4\alpha\,(2f_i - f_j) - 2\beta F\right]}{6}$$

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

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

Differentiating with respect to e_i, yields

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

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

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

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

$$f_i^B(F) = \frac{2+2\beta F+\delta(1-d^2)}{8\alpha}.$$

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.

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

Differentiating with respect to e_i, yields

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

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

$$\tilde{e}_i^{B,F} = \frac{1}{4}\theta(1-d)(2+(d-1)\delta).$$

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

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

which entails $f_i^B = \frac{d((d-2)\delta+2)+\delta+2}{8\alpha}$.

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

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

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

$$\tilde{e}_i = \frac{\theta(2-\delta)}{4}, \quad \tilde{x}_i = \frac{\theta(\delta+2g)}{4}, \quad F = 0, \quad f_i = \frac{\delta+2}{8\alpha} \quad \text{and} \quad t_i = \frac{1}{4\alpha}$$

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

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

Differentiating with respect to e_i, yields

$$\frac{\theta(2-\beta F)\left[\delta(4\beta F-2)+9\right] - 18e_i - 9e_j}{18\theta} = 0$$

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

$$e_i(e_j) = \begin{cases} \frac{1}{18}[\theta(2-\beta F)(\delta(4\beta F-2)+9] - \frac{1}{2}e_j, & \text{if } e_j < \frac{\theta(2-\beta F)[\delta(4\beta F-2)+9]}{9} \\ 0 \ \ \text{otherwise.} \end{cases}$$

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

$$\tilde{e}_i = \frac{\theta(2-\beta F)[\delta(4\beta F-2)+9]}{27}$$

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,

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

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

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

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

$$\tilde{e}_i^{B,IN} = \frac{1}{18}\theta\left[9 - 2\delta(2-\beta F)(1 + \beta F - 3d) - 9d\right].$$

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

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

where $G \equiv \left[\delta\left(\delta(5-3d)^2 + 24d - 12\right) + 9\right]^{1/2}$. Fine F^* positive for all β values, and the second-period appropriation in equilibrium is

$$\tilde{x}_i^{B,IN} = \frac{\theta\left[3 - (3d-5)\delta - G - 3\right]}{14\delta}\left[(d+g) - \frac{((9-11d)\delta + G - 3)\left((3d-5)\delta + G - 3\right)}{98\delta}\right].$$

9.10.2 Both R and AO are present

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

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

Differentiating with respect to e_i, we obtain

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

Then, solving for x_i, we obtain a best response function.

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

Simultaneously solving for e_i and e_j, we obtain the equilibrium extraction,

$$\tilde{e}_i(f_i, f_j, F) = \frac{\left[\theta(1+g) - E\right](2\alpha I(2f_i - f_j) - 2 + \beta F)}{3}$$

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

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

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

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, yields

$$\frac{1}{18\theta}[\theta(\beta F-2)(9+4\beta F-2\delta) - 2\alpha\theta\left[f_i\left(9-2\delta\alpha f_j+\delta\beta F-8\delta\right) - \delta f_j\left(10-10\alpha f_j+\beta F\right)\right]$$

$$-18e_i - 9c^2e_j - 16\delta\theta\alpha^2I^2f_i2] = 0$$

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

$$e_i(e_j) = \begin{cases} \frac{\theta(2-\beta F)(9-2\delta+4\delta\beta F)-2\alpha\theta\left(f_i(9-8\delta-2\delta\alpha f_j+\delta\beta F)+\delta f_j(\beta F-10\alpha f_j+10)+8\delta\alpha f_i^2\right)}{18} - \frac{e_j}{2}, \\ \text{if } e_j < \frac{\theta(2-\beta F)(9-2\delta+4\delta\beta F)-2\alpha\theta\left(f_i(9-8\delta-2\delta\alpha f_j+\delta\beta F)+\delta f_j(\beta F-10\alpha f_j+10)+8\delta\alpha f_i^2\right)}{9} \\ 0 \quad \text{otherwise.} \end{cases}$$

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

$$\tilde{e}_i = \frac{\theta}{27}[2\alpha(f_j\left[9+2\delta\alpha f_i - \delta(\beta F+28)\right] - f_i\left[18+26\delta\alpha f_i+\delta(\beta F-26)\right] + 28\delta\alpha f_j^2)$$
$$+(2-\beta F)(9-2\delta+4\delta\beta F)]$$

Second period, the artisanal organization chooses quotas and fines that maximize joint profits, yielding the following results.

Differentiating the artisanal's organization problem with respect to e_i, yields

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

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

$$\tilde{e}_i = \frac{\theta\left[9+2\delta\alpha\left(f_i+f_j\right)\left[\alpha\left(f_i+f_j\right)+2\delta\beta F-1\right]+2(\beta F-2)(\beta F+1)\right]}{18}.$$

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

$$f_i = \frac{\delta-9-8\delta\beta F+3\sqrt{9+12\delta\beta F+(\delta+2\delta\beta F)^2}}{4\delta\alpha}.$$

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

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

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

$$1 - \frac{e_i+e_j}{\theta} + \frac{d\delta\left(\delta+2\beta\delta F - \sqrt{(\delta+2\beta\delta F)^2+12\beta\delta F+9}+2\right)}{\delta}$$
$$\frac{2\beta\delta F\left(\delta+2\beta\delta F - \sqrt{(\delta+2\beta\delta F)^2+12\beta\delta F+9}+6\right) - 3\sqrt{(\delta+2\beta\delta F)^2+12\beta\delta F+9}+9}{\delta} = 0$$

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

$$\begin{aligned}\hat{e} &= \frac{\theta}{2\delta}\times\left[9+(\delta-3\sqrt{9+12\delta\beta F+(\delta+2\delta\beta F)^2}+12\delta\beta F)\right. \\ &\quad \left.+2\delta\beta IF(\delta-\sqrt{9+12\delta\beta F+(\delta+2\delta\beta F)^2}+2\delta\beta F)\right]\end{aligned}$$

Setting it equal to the equilibrium first-period appropriation, $e_i^{B,IN}$, we find $F^{B,IN} = \frac{4\delta-5}{4\beta\delta}$. Therefore, the organization's fine is

$$f_i^{B,IN} = \frac{2-14\delta+3D}{8\alpha\delta}$$

where $D \equiv 6\delta - 1$.

9.11 *Proof of Corollary 3*

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

$$\begin{aligned}FPI^R &= \tilde{e}_i^{R,IN} - \tilde{e}_i^{R,F} \\ &= \left[\frac{1}{98}\left(36-\sqrt{9d^2-6d+22}-d\left(4\sqrt{9d^2-6d+22}+12d-1\right)\right)\theta - \frac{\theta}{4}(1-d)(2-(1-d))\right] \\ &= \frac{1}{196}\left[23-2\sqrt{9d^2-6d+22}+d\left(2-8\sqrt{9d^2-6d+22}+25d\right)\right]\theta\end{aligned}$$

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

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, $e_i^{AO,IN} > e_i^{AO,F}$,

$$\begin{aligned} e_i^{AO,IN} - e_i^{AO,F} &= \frac{\theta[10 - 3\sqrt{10}]}{2} - \frac{\theta}{4} \\ &= \frac{1}{4}\left(19 - 6\sqrt{10}\right)\theta \end{aligned}$$

which is positive for all $\theta > 0$. Therefore, $\tilde{e}_i^{AO,IN} > \tilde{e}_i^{AO,F}$, which implies that $FPI^{AO} > 0$ in this regulatory setting too.

When both AO and R are present, the difference between first-period appropriation levels is

$$\begin{aligned} FPI^B &= \tilde{e}_i^{B,IN} - \tilde{e}_i^{B,F} \\ &= \frac{\theta}{4} - \frac{\theta}{4}(1-d)(2-(1-d)) \\ &= \frac{d^2\theta}{4} \end{aligned}$$

which is positive for all admissible values of $theta$ and d. Therefore, $\tilde{e}_i^{B,IN} > \tilde{e}_i^{B,F}$, implying that $FPI^B > 0$ in this regulatory setting as well.

Second-period appropriation. When only the R is present, we find that

$$\begin{aligned} SPI^R &= \tilde{x}_i^{R,F} - \tilde{x}_i^{R,IN} \\ &= \frac{\theta}{4}(1-d)\left(2(d+g)-(1-d)^2\right) - \frac{1}{686}\left(8 - \sqrt{9d^2-6d+22} - 3d8\right)\left(49g + \sqrt{22} + 13\right)\theta \\ &= \frac{1}{686}\left(\sqrt{9d^2-6d+22} + 3d - 8\right)\left(49g + \sqrt{22} + 13\right)\theta + \frac{1}{4}(1-d)\theta\left(d^2+2g+1\right) \end{aligned}$$

solving by d, we obtain that the admissible cutoff is $d = 1$, which implies that the expression above positive for all admissible values of g and d. Therefore, $SPI^R > 0$ for all g and d.

When AO is present, we obtain that

$$\begin{aligned} SPI^{AO} &= \tilde{x}_i^{AO,F} - \tilde{x}_i^{AO,IN} \\ &= \frac{1}{4}\theta(2g) - \frac{\left(4-\sqrt{10}+\delta\right)\left(3\sqrt{10}+g-9\right)\theta}{2} \\ &= \frac{1}{4}\left[2\left(\sqrt{10}-3\right)g - 42\sqrt{10} + 133\right]\theta \end{aligned}$$

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

When both AO and R are present, we obtain that

$$\begin{aligned} SPI^B &= \tilde{x}_i^{B,F} - \tilde{x}_i^{B,IN} \\ &= \frac{\theta}{4}(1-d)\left(2(d+g)-(d-1)^2\right) - \frac{1}{4}(2g+1)\theta \\ &= -\frac{1}{4}d\theta[1-(1-d)d+2g] \end{aligned}$$

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

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

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

which is positive for all $d > 0$. In contrast, $\tilde{e}_i^{R,F} = \tilde{e}_i^{B,F}$ for all parameter values. Similarly, for second-period appropriation, we find that

$$\begin{aligned}
\tilde{x}_i^{R,F} - \tilde{x}_i^{AO,F} &= \left[\frac{1}{4}(d-1)\theta\left(d^2+2g+1\right)\right] - \left[\frac{1}{4}(2g+1)\theta\right] \\
&= \frac{1}{4}d\theta[(1-d)d - 2g - 1]
\end{aligned}$$

which is negative for all $d > 0$. Therefore $\tilde{x}_i^{AO,F} > \tilde{x}_i^{R,F}$ for all admissible parameter values. However, $\tilde{x}_i^R = \tilde{x}_i^B$ holds under all parameter values.

9.12 *Proof of Corollary 4*

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

$$\begin{aligned}
\widetilde{FPI}^R - \widetilde{FPI}^{AO} &= \frac{1}{196}\left(23 - 2\sqrt{9d^2-6d+22} + d\left(-8\sqrt{9d^2-6d+22} + 25d + 2\right)\right)\theta - \frac{1}{4}\left(19 - 6\sqrt{10}\right)\theta \\
&= \frac{1}{196}\left(294\sqrt{10} - 2\sqrt{9d^2-6d+22} + d\left(-8\sqrt{9d^2-6d+22} + 25d + 2\right) - 908\right)\theta
\end{aligned}$$

which is positive if and only if $d < \breve{d}$, where

$$\breve{d}(\delta) \equiv 11 - 4\sqrt{10} + \sqrt{157 - 48\sqrt{10}} \approx 0.633579$$

This implies that $\widetilde{FPI}^R > \widetilde{FPI}^{AO}$ if $d < d^*$. Otherwise, $\widetilde{FPI}^R < \widetilde{FPI}^{AO}$.

Comparing $\widetilde{FPI}^R$ now against $\widetilde{FPI}^B$, we find that

$$\begin{aligned}
\widetilde{FPI}^R - \widetilde{FPI}^B &= \frac{1}{196}\left(23 - 2\sqrt{9d^2-6d+22} + d\left(-8\sqrt{9d^2-6d+22} + 25d + 2\right)\right)\theta - \frac{d^2\theta}{4} \\
&= \frac{1}{196}\left(23 - 2\sqrt{9d^2-6d+22} - 2d\left(4\sqrt{9d^2-6d+22} + 12d - 1\right)\right)\theta.
\end{aligned}$$

which is positive if and only if $d < \bar{d}$, where $\bar{d} \equiv \frac{1}{8}\left(\sqrt{13} - 1\right) \approx 0.325694$. Therefore, $\widetilde{FPI}^R > \widetilde{FPI}^B$ if and only if $d < \bar{d}$. Otherwise, the relationship is $\widetilde{FPI}^R < \widetilde{FPI}^B$.

And comparing $\widetilde{FPI}^{B}$ against $\widetilde{FPI}^{AO}$, we obtain that

$$\begin{aligned}\widetilde{FPI}^{B}-\widetilde{FPI}^{AO} &= \frac{d^2\theta}{4}-\frac{1}{4}\left(19-6\sqrt{10}\right)\theta \\ &= \frac{1}{4}\left(d^2+6\sqrt{10}-19\right)\theta\end{aligned}$$

which is positive if and only if $d>\hat{d}$, where $\hat{d}\equiv\sqrt{10}-3\approx 0.162278$, which means that $\widetilde{FPI}^{B}>\widetilde{FPI}^{AO}$ if $d>\hat{d}$. Otherwise, $\widetilde{FPI}^{B}<\widetilde{FPI}^{AO}$.

Finally, comparing $\widetilde{FPI}^{R}>FPI^{R}$, we obtain

$$\begin{aligned}\widetilde{FPI}^{R}-FPI^{R} &= \left[\frac{1}{686}\left(\sqrt{9d^2-6d+22}+3d-8\right)\left(49g+\sqrt{22}+13\right)\theta+\frac{1}{4}(1-d)\theta\left(d^2+2g+1\right)\right] \\ &\quad -\left[\frac{\left(98\left(\sqrt{22}-1\right)g+10\sqrt{22}+179\right)\theta}{1372}\right] \\ &= \frac{\theta}{1372}\Big[343(1-d)\left(d^2+2g+1\right)+2\left(\sqrt{9d^2-6d+22}+3d-8\right)\left(49g+\sqrt{22}+13\right) \\ &\quad +98\left(1-\sqrt{22}\right)g-10\sqrt{22}-179\Big]\end{aligned}$$

which is negative for all $d>0$. Therefore, $FPI^{R}>\widetilde{FPI}^{R}$ for all admissible parameter values. In contrast, $FPI^{AO}=\widetilde{FPI}^{AO}$ and $\widetilde{FPI}^{B}>FPI^{B}$, given that $\widetilde{FPI}^{B}>0$ and $FPI^{B}=0$, for all parameter values.

9.13 *Proof of Corollary 5*

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

$$\begin{aligned}\widetilde{SPI}^{R}-\widetilde{SPI}^{B} &= \left[\frac{1}{686}\left(\sqrt{9d^2-6d+22}+3d-8\right)\left(49g+\sqrt{22}+13\right)\theta+\frac{1}{4}(1-d)\theta\left(d^2+2g+1\right)\right] \\ &\quad -\left[\frac{1}{4}d\theta((1-d)d-2g-1)\right]\end{aligned}$$

solving for $d(g)$ the cutoff becomes

$$d(g)=\frac{196g\left(\left(2\sqrt{22}+23\right)g+2\sqrt{22}+17\right)+134\sqrt{22}+125}{36\left(49g+\sqrt{22}+13\right)}$$

which is positive for all admissible (d,g) pairs, entailing that $\widetilde{SPI}^{R}>\widetilde{SPI}^{B}$ holds under all admissible parameters.

Comparing now $\widetilde{SPI}^{B}$ and $\widetilde{SPI}^{AO}$, we find that

$$\begin{aligned}
\widetilde{SPI}^{B}-\widetilde{SPI}^{AO} &= \left[\frac{1}{4}d\theta((1-d)d-2g-1)\right]-\left[\frac{1}{4}\left(2\left(\sqrt{10}-3\right)g-42\sqrt{10}+133\right)\theta\right] \\
&= \frac{1}{4}\theta\left(d^2-d^3-2\left(d+\sqrt{10}-3\right)g-d+42\sqrt{10}-133\right)
\end{aligned}$$

solving for $d(g)$, the cutoff becomes

$$\begin{aligned}
d(g) &= \frac{\sqrt[3]{144g-54\sqrt{10}g+2\sqrt{8(3g+1)^3+\left(9\left(3\sqrt{10}-8\right)g-567\sqrt{10}+1799\right)^2}+1134\sqrt{10}-3598}}{3\sqrt[3]{2}} \\
&+\frac{1}{3}-\frac{2\sqrt[3]{2}(3g+1)}{3\sqrt[3]{144g-54\sqrt{10}g+2\sqrt{8(3g+1)^3+\left(9\left(3\sqrt{10}-8\right)g-567\sqrt{10}+1799\right)^2}+1134\sqrt{10}-3598}}
\end{aligned}$$

which is negative for all admissible (d,g) pairs. Therefore, $\widetilde{SPI}^{B}-\widetilde{SPI}^{AO}$ is negative, which implies that $\widetilde{SPI}^{AO}>\widetilde{SPI}^{B}$ for all admissible parameters.

Comparing now $\widetilde{SPI}^{R}$ and $\widetilde{SPI}^{AO}$, we find that

$$\begin{aligned}
\widetilde{SPI}^{R}-\widetilde{SPI}^{AO} &= \left[\left(\frac{1}{686}\left(\sqrt{9d^2-6d+22}+3d-8\right)\left(49g+\sqrt{22}+13\right)\theta+\frac{1}{4}(1-d)\theta\left(d^2+2g+1\right)\right)\right] \\
&-\left[\frac{1}{4}\left(2\left(\sqrt{10}-3\right)g-42\sqrt{10}+133\right)\theta\right]
\end{aligned}$$

solving for $d(g)$, the cutoff becomes

$$\begin{aligned}
d^*(g) &= 48\left(4325\sqrt{22}-3900253\sqrt{10}-2744\sqrt{55}+12333665\right) \\
&g\Big[49g\Big(g\left[g\left(49g(7g+2)+1372\sqrt{10}-12\sqrt{22}-3635\right)-28616\sqrt{10}+20\sqrt{22}+90518\right] \\
&+68\sqrt{22}-10896\sqrt{10}-48\sqrt{55}+34547\Big)+15891484\sqrt{10}-86864\sqrt{22}+55664\sqrt{55}-50278976\Big]
\end{aligned}$$

meaning that, to the left-hand of the upward sloping curve, $d<d^*(g)$, that $\widetilde{SPI}^{R}>\widetilde{SPI}^{AO}$, but to the right-hand of the upward sloping curve, $d>d^*(g)$, we have that $\widetilde{SPI}^{R}<\widetilde{SPI}^{AO}$.

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

$$\begin{aligned}
\widetilde{SPI}^{R}-SPI^{R} &= \left[\frac{1}{686}\left(\sqrt{9d^2-6d+22}+3d-8\right)\left(49g+\sqrt{22}+13\right)\theta+\frac{1}{4}(1-d)\theta\left(d^2+2g+1\right)\right] \\
&-\left[\frac{\left(98\left(\sqrt{22}-1\right)g+10\sqrt{22}+179\right)\theta}{1372}\right] \\
&= \frac{\theta}{1372}\Big[343(1-d)\left(d^2+2g+1\right)+2\left(\sqrt{9d^2-6d+22}+3d-8\right)\left(49g+\sqrt{22}+13\right) \\
&+98\left(1-\sqrt{22}\right)g-10\sqrt{22}-179\Big]
\end{aligned}$$

which is negative for all d and g admissible parameter values. Therefore, $SPI^R > \widetilde{SPI}^R$ for all admissible parameter values. In contrast, $SPI^{AO} = \widetilde{SPI}^{AO}$ and $\widetilde{SPI}^B < SPI^B$, given that $\widetilde{SPI}^B < 0$ and $SPI^B = 0$, for all parameter values.

9.14 *Proof of Corollary 6*

As a reference, we first evaluate total inefficiencies in the base model (where $d = 0$). Under AO, total inefficiencies are $TI^{AO} = \frac{1}{2}\theta\left[\left(\sqrt{10}-3\right)g - 24\sqrt{10} + 76\right]$, under R they are $TI^R = \frac{\left(98\left(\sqrt{22}-1\right)g - 4\sqrt{22}+683\right)\theta}{1372}$, and under B they are zero since first- and second-period inefficiencies are nil, $TI^B = 0$.

Comparing TI^R and TI^{AO}, we obtain

$$\begin{aligned} TI^R - TI^{AO} &= \left[\frac{\theta\left(98\left(\sqrt{22}-1\right)g - 4\sqrt{22}+683\right)}{1372}\right] - \left[\frac{1}{2}\theta\left[\left(\sqrt{10}-3\right)g - 24\sqrt{10}+76\right]\right] \\ &= \frac{\theta\left[98\left(20-7\sqrt{10}+\sqrt{22}\right)g + 16464\sqrt{10} - 4\sqrt{22} - 51453\right]}{1372} \end{aligned}$$

which is positive for all admissible values of θ and g. Therefore, $TI^R > TI^{AO}$ for all parameter values. Since $TI^R, TI^{AO} > 0$ but $TI^B = 0$, the total inefficiency ranking is $TI^R > TI^{AO} > TI^B = 0$.

When $d > 0$, total inefficiencies under AO coincide with those when $d = 0$, that is, $\widetilde{TI}^{AO} = TI^{AO}$. Under R, however, total inefficiencies become

$$\begin{aligned} \widetilde{TI}^R &= \frac{\theta}{1372}\Big[343(1-d)\left(d^2+2g+1\right) + 2\left(\sqrt{9d^2-6d+22}+3d-8\right)\left(49g+\sqrt{22}+13\right) \\ &\quad +7\left(23 - 2\sqrt{9d^2-6d+22} + d\left(-8\sqrt{9d^2-6d+22}+25d+2\right)\right)\Big] \end{aligned}$$

and under B, they become $\widetilde{TI}^B = -\frac{1}{4}d\theta\left[(d-1)^2+2g\right]$, which is negative for all parameter values and becomes zero at $d = 0$.

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

$$\begin{aligned} \widetilde{TI}^R - \widetilde{TI}^{AO} &= \Big(\frac{\theta}{1372}\Big[343(1-d)\left(d^2+2g+1\right) + 2\left(\sqrt{9d^2-6d+22}+3d-8\right)\left(49g+\sqrt{22}+13\right) \\ &\quad +7\left(23 - 2\sqrt{9d^2-6d+22} + d\left(-8\sqrt{9d^2-6d+22}+25d+2\right)\right)\Big]\Big) - \Big(\frac{1}{2}\theta\Big[76 \\ &\quad + \left(\sqrt{10}-3\right)g - 24\sqrt{10}+76\Big]\Big) \end{aligned}$$

which is positive if and only if $g > g^*(d)$, where

$$g^*(d) \equiv \frac{1}{98\left(4d - \sqrt{9d^2-6d+22} + 7\sqrt{10} - 20\right)}\Big[d\left(6\sqrt{22} - 56\sqrt{9d^2-6d+22} + 7d(74-49d) - 251\right) \\ +2\left(\sqrt{22}\sqrt{9d^2-6d+22} + 6\sqrt{9d^2-6d+22} + 8232\sqrt{10} - 8\sqrt{22} - 25920\right)\Big]$$

which, evaluated at $d = 0$, simplifies to $g^*(0) \simeq -0.994$. Therefore, when $d = 0$, condition $g > g^*(0)$ holds for all values of g, entailing that $\widetilde{TI}^R > \widetilde{TI}^{AO}$ also holds.

In summary, total inefficiencies satisfy $\widetilde{TI}^R > \widetilde{TI}^{AO} > 0 \geq \widetilde{TI}^B$ if $g > g^*(d)$ since $\widetilde{TI}^B < 0$. Otherwise, they satisfy $\widetilde{TI}^{AO} > \widetilde{TI}^R > 0 \geq \widetilde{TI}^B$. This ranking embodies that in the base model as a special case since, at $d = 0$, $\widetilde{TI}^R > \widetilde{TI}^{AO}$ holds for all parameter values, and $\widetilde{TI}^B$ collapses to zero.

Comparing $\left|\widetilde{TI}^R\right|$ and $\left|\widetilde{TI}^B\right|$, we obtain that

$$\left|\widetilde{TI}^R\right| - \left|\widetilde{TI}^B\right| = \Big|\frac{\theta}{1372}\Big[343(1-d)\left(d^2+2g+1\right) + 2\left(\sqrt{9d^2-6d+22} + 3d - 8\right)\left(49g + \sqrt{22} + 13\right) \\ +7\left(23 - 2\sqrt{9d^2-6d+22} + d\left(-8\sqrt{9d^2-6d+22} + 25d + 2\right)\right)\Big]\Big| - \left|\frac{1}{4}d\theta\left[(d-1)^2 + 2g\right]\right|$$

which is positive if and only if $g < g_R$, where

$$g_R = \frac{1}{49\left(\sqrt{9d^2-6d+22} - 11d - 1\right)}\Big[8\sqrt{22} - \sqrt{22}\left(\sqrt{9d^2-6d+22}\right) - 6\sqrt{9d^2-6d+22} \\ +d\left(28\sqrt{9d^2-6d+22} + 7d(49d-86) - 3\sqrt{22} + 297\right) - 148\Big]$$

Comparing $\left|\widetilde{TI}^{AO}\right|$ and $\left|\widetilde{TI}^B\right|$, we obtain that

$$\begin{aligned}\left|\widetilde{TI}^{AO}\right| - \left|\widetilde{TI}^B\right| &= \left|\frac{1}{2}\theta\Big[76 + \left(\sqrt{10}-3\right)g - 24\sqrt{10} + 76\Big]\right| - \left|\frac{1}{4}d\theta\left[(d-1)^2 + 2g\right]\right| \\ &= \frac{1}{4}\theta\left(152 - d\left((d-1)^2 + 2g\right) + 2\sqrt{10}g - 6g - 48\sqrt{10}\right)\end{aligned}$$

which is positive if and only if $g < g_{AO}$, where

$$g_{AO} \equiv \frac{d(d-1)^2 + 8\left(6\sqrt{10} - 19\right)}{2\left(\sqrt{10} - d - 3\right)}.$$

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