When Should the Regulator Be Left 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 these two regulatory agencies under a flexible policy regime, where quotas and fines can be revised across periods, and under an inflexible policy regime, where they cannot. We show that inefficiencies arise in the inflexible regime, but they are reduced when the two agencies coexist. Overall, we demonstrate that the artisanal organization may be preferred when environmental damages are low, but the regulator may be preferable otherwise.

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

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

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

Our setting considers two types of externalities: (i) a cost-related externality, since each fisherman does not internalize the cost increase that its appropriation entails on other fishermen; and (ii) a third-party externality, originating from the biodiversity loss of appropriation decisions. The AO only considers the first form of externality, while the R considers both types. As a benchmark, we first examine a context where regulatory agencies can easily revise their policies across periods ("flexible" policy regime), showing that no inefficiencies arise when R is present, yielding a first-best outcome. However, inefficiencies exist when only AO is active, because this agency ignores the second form of externality. When appropriation does not generate biodiversity losses, the second type of externality is absent, and all regulatory agencies give rise to first-best outcomes. CPRs in countries such as Japan or Chile, where quotas are often revised and closely monitored, would be closer to a flexible regime; as described in Cancino et al. (2007). In this context, the R's presence (with or without AO) can induce socially optimal appropriation levels, not giving rise to inefficiencies. These results also apply to other CPRs, such as aquifers or groundwater, where managers often have local control (e.g., Groundwater Management Districts), but there are also state or federal regulatory bodies seeking to conserve water. For more examples, see the review article by Edwards and Guilfoos (2021).

When regulatory agencies cannot adjust quotas and fines across periods ("inflexible" policy regime), we demonstrate that inefficiencies arise, since they do not induce socially optimal appropriations in each period. Intuitively, these agencies have a single policy tool to use across all periods, setting a linear combination of the quotas they would have set in the first- and second-period under a flexible policy regime. Regulatory behavior under an inflexible policy regime resembles landowners' water use in the open-loop equilibrium in Negri (1989), where participants do not update their pumping rates across time (although water use can change); as opposed to that in the feedback equilibrium, where they update these rates in each period.[1]

We measure these inefficiencies as the difference in equilibrium welfare levels between the inflexible and flexible regime and, next, compare equilibrium appropriation between these two regimes. First, we show that, with inflexible regimes, no regulatory agency can, on its own, fully internalize all externalities, implying that the inflexible regime, despite being welfare improving relative to no regulation, gives rise to *regulatory* inefficiencies, as they arise because regulatory agencies cannot revise their quotas/fines across periods. Our results not only apply to developing countries suffering from slow policy revisions, but also to countries where fishing quotas are revised every year (such as total allowable catch in the EU). 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).

The above finding entails that the inflexible R yields a suboptimal outcome and a natural question is whether the inflexible AO or B can induce appropriation levels that are closer to the first best, thus being preferable. We demonstrate that welfare comparisons and appropriation differentials depend on the severity of the third-party externality. When biodiversity loss is relatively small, the presence of AO yields the smallest inefficiencies in both periods, generating the highest welfare. Overall, our results suggest that, when agencies exhibit similar objectives, the AO's presence is unambiguously welfare improving, giving rise to smaller inefficiencies when operating alone, or helping reduce the R's inefficiencies due to the inflexible policy regime. Alternatively, this finding entails that, if the R's administrative costs are higher than the AO's, it should refrain from operating in CPRs when both agencies have similar objective functions, letting the AO do "all the work," especially in settings where the R cannot easily revise quotas and fines across periods. This is the case, for instance, of CPRs in Vietnam, Indonesia, or Sri Lanka where policies, despite being often updated, are rarely monitored; as reported in Atapattu (1987), Harkes and Novaczek (2002), Lai (2008), and Quynh et al. (2017). However, when the biodiversity loss becomes more severe, the R gives rise to the highest aggregate welfare, implying that he should be left alone in the commons. Intuitively, the R generates less inefficiencies than both agencies (B) because, in this case, the R starts setting a more stringent aggregate quota to account for severe biodiversity losses. The AO, however, ignores these losses and responds relaxing the individual quotas to its members, ultimately giving rise to more inefficiencies.

We also show that faster regeneration rates emphasize the above results, making the third-party externality more severe, and thus expanding the settings under which having only R is socially

[1] Nonetheless, the open-loop equilibrium settings in Negri (1989), where actors can commit to different harvest caps in future periods (but do not update caps), is not exactly analogous to the inflexible policy regime in our paper, where the regulator must commit to a single harvest cap for all future periods. In the open-loop equilibrium, pumping rates can vary across periods, while they coincide in all periods in the inflexible regime.

preferable. This case includes pelagics, such as Bigeye scad, Pacific herring or Sockeye salmon, which regenerate rapidly. In contrast, when regeneration rates are slow, it is more likely that the AO or B become socially preferred, which may apply to mollusks, the Pacific ocean perch, or the Sablefish.[2]

Related literature. Since Hardin (1968), several studies have examined socially excessive exploitation in CPRs; for a literature review, see Faysse (2005). 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— such as Boyce (2000), Danielsson (2000), Cancino et al. (2007), Arnason (2009), Zhou and Segerson (2016), and Isaksen and Richter (2019). However, we analyze equilibrium appropriation when different agencies manage the resource, allowing for flexible and inflexible policy regimes, and also letting R and AO exhibit different objective functions. The case of similar objectives between R and AO has been extensively studied since Ostrom (1990), showing that AOs can efficiently manage the resource. Zhou and Segerson (2016) also analyze 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 examine how different group policies can lead firms to behave closer to the social optimum, thus internalizing an externality they impose on third agents. Our paper considers one of their group policies, the "Proportional Tax with Allowable Group Limit," where the tax is paid only when aggregate appropriation exceeds a quota, but this tax is designed to help firms internalize an externality that they only impose on third agents (consumers), not considering within-group (cost) externalities. 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.[3]

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

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

Other related papers include Huang and Smith (2014), which empirically estimates the CPRs inefficiencies comparing current and socially optimal exploitation paths; or Cash et al. (2006), which argues that institutions with different hierarchies (such as the R and AO) may be beneficial for fishermen at coordinating their decisions.[4] 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. As a benchmark, section 3 presents equilibrium behavior under no regulation. 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, 1 and 2, during two periods. The initial stock of the CPR is exogenously given and denoted by $\theta > 0$. Each fisherman i extracts a first-period amount $e_i \in [0, 1]$, where $i = \{1, 2\}$. The market price is given, and normalized to 1, and fisherman i's first-period extraction cost is

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

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

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

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

and

$$\pi_i^{1,R} = e_i - \frac{e_i(e_i + e_j)}{\theta} - \beta \frac{F}{2}(e_i + e_j - \hat{e}) \tag{3}$$

where α (β) denotes the probability that fisherman i is monitored by the AO (R, respectively), and α, $\beta \in [0, 1]$. Fisherman i is found liable by the AO if and only if his extraction exceeds his

[4] For an extensive review of the literature on group incentives in fisheries, see Holland (2018), and more generally in natural resource management and environmental regulation, see Segerson (2022). For a review on polycentric institutions (nested governance), see Ostrom (2010, 2012).

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

assigned quota, $e_i > \overline{e}_i$, entailing a penalty $f_i \geq 0$. Otherwise, he faces no penalty or subsidy.[6]

Similarly, he is found liable by the R if and only if aggregate extraction exceeds the quota, $e_i + e_j > \hat{e}$, each fisherman paying a penalty $F/2$.[7] Since fishermen are cost symmetric, this setting is equivalent to one where the R evenly shares this quota among them.

If fisherman i faces both the AO and R, his first-period profit is

$$\pi_i^{1,B} = \pi_i^{1,AO} - \beta \frac{F}{2}(e_i + e_j - \hat{e}) \tag{4}$$

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

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

$$c^2(x_i, x_j, \theta, E) = \frac{x_i(x_i + x_j)}{\theta(1+g) - E} \tag{5}$$

where $E \equiv e_i + e_j$ denotes first-period aggregate appropriation, and x_i is fisherman i's second-period extraction. Note that the available stock at the beginning of the second period is $\theta(1+g) - E$, and $g \in \left[0, \frac{E}{\theta}\right]$ represents the growth rate of the initial stock. When $g = 0$, the initial stock θ does not regenerate, implying that fishermen face a stock $\theta - E$ at the beginning of the second period. In contrast, when $g = \frac{E}{\theta}$, the stock is fully recovered, so the initial stock θ is the same at the beginning of the second period. We consider that regeneration rate is not excessive, $g < \frac{4-3\delta}{8}$, where $\delta \in (0, 1]$ is the discount factor which coincides across all players. Otherwise, the resource would regenerate rapidly, making the role of regulation less necessary. Hence, second-period profits when facing the AO (R) are

$$\pi_i^{2,AO} = x_i - \frac{x_i(x_i + x_j)}{\theta(1+g) - E} - \alpha t_i \left(x_i - \overline{e}_i\right) \tag{6}$$

and

$$\pi_i^{2,R} = x_i - \frac{x_i(x_i + x_j)}{\theta(1+g) - E} - \beta \frac{T}{2}(x_i + x_j - \hat{e}) \tag{7}$$

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

[6] The above profit function allows for fisherman i's extraction to fall below his assigned quota, $e_i < \overline{e}_i$, thus receiving a subsidy. However, we show that, in equilibrium, this does not occur and, instead, fishermen choose to fish at the quota.

[7] For instance, Wanchana et al. (2016) discuss standard operating procedures for sharks and rays' data collection used by Southeast Asian governments, including sampling at landing sites (such as sampling size, sampling days, and the selection of boats). Sampling at landing sites and sampling on board is also frequently used in other fisheries, such as large pelagic, lingcod, dogfish, skate, sole, flounder, cod, and rockfish in the Pacific region; see Department of Fishery and Oceans (2006a,b).

at the beginning of the second period ("flexible" policy) and are denoted as $\bar{e}_i$ and $\overline{x}_i$ for the AO, and $\hat{e}$ and $\widehat{x}$ for the R. (Next sections analyze both flexible and inflexible policy regimes.) The profit from facing both regulatory agencies, $\pi_i^{2,B}$, is

$$\pi_i^{2,B} = \pi_i^{2,AO} - \beta\frac{T}{2}(x_i + x_j - \hat{e}). \tag{8}$$

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

We finally present the objective function of each regulatory agency. When appropriation does not entail biodiversity losses, R and AO have the same objective function, implying that every regulatory setting $k = \{AO, R, B\}$ maximizes the sum of discounted joint profits

$$\left(\pi_i^{1,k} + \delta\pi_i^{2,k}\right) + \left(\pi_j^{1,k} + \delta\pi_j^{2,k}\right) \tag{9}$$

plus the sum of discounted fines from both firms. When biodiversity losses are present, the AO still considers (8), but the R now maximizes the sum of discounted joint profits and the discounted biodiversity loss

$$\left(\pi_i^{1,R} + \delta\pi_i^{2,R}\right) + \left(\pi_j^{1,R} + \delta\pi_j^{2,R}\right) - d\left(E + \delta X\right) \tag{10}$$

plus the sum of discounted fines, where $d \geq 0$ captures the (constant) marginal social damage from appropriation, e.g., biodiversity loss. When $d = 0$, both regulatory agencies have the same objective function; and when $d > 0$ the R prefers lower appropriation levels than the AO.

In summary, when $d = 0$, there is a single externality –namely, the cost externality between fishermen– that regulatory agencies (R, AO, or both) seek to address. However, when $d > 0$, the AO only considers a cost externality while the R seeks to curb two externalities (the cost externality and that arising from biodiversity loss).

3 Equilibrium Analysis without Regulation

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

1. In the first stage, every fisherman i simultaneously and independently chooses his first-period appropriation, e_i.

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

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

$$\max_{x_i \geq 0} \quad \pi_i^{2,NR} = x_i - \frac{x_i(x_i + x_j)}{\theta(1+g) - E} \tag{11}$$

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

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

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

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

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

$$\max_{e_i \geq 0} \; \pi_i^{1,NR} + \delta \pi_i^{2,NR}(x_i^{NR}(E), x_j^{NR}(E)) \tag{12}$$

where $\pi_i^{1,NR}$ denotes first-period profits without regulation.

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

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

which are both positive under all parameter values.

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

4 Flexible policy

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

1. In the first period:

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

[8] The initial condition on g, $g < \frac{E}{\theta}$, holds in this setting if $g < \frac{4(9-2\delta)}{27}$. This cutoff lies above 1 for all admissible values of δ, which applies to a wide range of fish species, both those exhibiting relatively high and low regeneration rates, such as the Orange Roughy, see Mace et al. (1990); the Atlantic cod, see Lilly et al. (2008); and the Atlantic bluefin tuna, see Jelić Mrčelić et al. (2023).

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

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

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

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

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

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

(c) If both AO and R are present, the R chooses a second-period aggregate extraction quota, $\widehat{x}$, 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.

Then, the time structure of the game technically has four stages when a single regulatory agency $k = \{R, AO\}$ is present: the first stage corresponds to points 1(a)-(b), where regulatory agency k selects first-period quotas and fines; the second stage corresponds to point 1(d), where fishermen respond with their first-period appropriation; the third stage corresponds to points 2(a)-(b), where regulatory agency k chooses second-period quotas and fines; and the fourth stage corresponds to point 2(d), where fishermen respond with their second-period appropriation levels. When both agencies are present (B), one more stage occurs at the beginning of the first and second period, where the R selects quota and fine and the AO responds setting its own in each period, see points 1(c) and 2(c), thus becoming a six-stage game.

Under a flexible policy, we next find the same first- and second-period equilibrium appropriation levels for every regulatory agency $k = \{R, AO, B\}$. For simplicity, we focus on settings where fishermen appropriate at their quotas.[10] As shown in the proof of Proposition 2, this technically

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

[10] Fishermen are penalized when appropriating above their quota, and they are not subsidized when appropriating below their quota. Penalties are set endogenously, inducing fishermen to appropriate at exactly their quotas.

means that, solving the game by backward induction, we identify: (i) the appropriation level of every fisherman i under a given regulatory agency k; (ii) the appropriation level that agency k seeks to induce; and (iii) anticipating the appropriation level in (i), we find the fines that induce fishermen to choose appropriations in (ii).[11]

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

$$e_i^{k,F} = \frac{\theta(1-d)\left[4-\delta(1-d)\right]}{16} \quad \text{and} \quad x_i^{k,F} = \frac{\theta(1-d)\left[4+8g+\delta+d(4-\delta(2-d))\right]}{32}$$

under regulatory setting $k = \{R, B\}$, being unambiguously decreasing in d; and

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

which satisfy $e_i^{k,F} > x_i^{k,F}$ in every k. In addition, first- and second-period fines are:

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

b) $F^R = \frac{4+\delta+d[12-\delta(6-5d)]}{8\beta}$ *and* $T^R = \frac{1+3d}{2\beta}$ *under R; and*

c) $f_i^B = \frac{d((d-2)\delta+4)+4+\delta}{16\alpha}$, $t_i^B = \frac{1+d}{4\alpha}$, $F^B = \frac{d[2-(1-d)\delta]}{2\beta}$, *and* $T^B = \frac{d}{\beta}$ *under B.*

The monitoring probabilities, α and β, decrease the severity of the equilibrium fines from AO and R, respectively, inducing fishermen to appropriate at the quota level. In other words, quotas and fines induce fishermen to choose an equilibrium appropriation in Proposition 2 that coincides with the appropriation level that regulator k seeks to induce in each period. Hence, appropriation is not affected by monitoring probabilities in equilibrium. For presentation purposes, we next evaluate the above equilibrium results when only cost externalities are present, $d = 0$.

Corollary 1. When $d = 0$, *first- and second-period equilibrium appropriation levels are*

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

for every regulatory setting $k = \{R, AO, B\}$, and first- and second-period fines are:

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

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

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

[11] Intuitively, the appropriation level that agency k seeks to induce can be interpreted as the quota. Therefore, firms are induced to stay at the quota in equilibrium, implying that the equilibrium appropriation levels reported throughout the paper (for each regulatory agency and for each policy regime) coincide with the quota that regulatory agency k seeks to induce.

In this context, appropriation levels with regulation are lower than under no policy in the first period, $e_i^{k,F} < e_i^{NR}$, but higher in the second period, $x_i^{k,F} > x_i^{NR}$, which holds for all admissible parameter values. Along with $e_i^k > x_i^k$, we obtain a complete ranking of exploitation levels with and without regulation,

$$x_i^{NR} < x_i^{k,F} < e_i^{k,F} < e_i^{NR} \tag{13}$$

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.

Insert here 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, 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 (i.e., the first-best level that the R seeks to achieve).[12]

When biodiversity loss is more severe (d increases), e_i^{NR} and $e_i^{AO,F}$ are unaffected but $e_i^{k,F}$ decreases for all $k = \{R, B\}$, thus expanding the reduction in first-period appropriation when R is present as he needs to address a larger third-party externality. This indicates that the AO alone, while addressing the cost-externality, cannot induce the first-best outcomes that only arise under R and B, yielding suboptimal results.

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.[13] Hence, the time structure of the game presented in Section 4 simplifies, since first-period regulation stays in place during the second period and every fisherman i responds choosing their appropriation level, x_i.

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

[12] 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.

[13] For instance, the Red Snapper quota in the Gulf of Mexico is only revised every 5 years, as reported by Gulf of Mexico Fishery Management Council (2013). In addition, the Chignik Salmon cooperative in Alaska did not revise its quotas between 2002 and 2004, as reported by Deacon et al. (2013). For a review of management activities in 67 fishing cooperatives in both developed and developing countries, see Ovaldo et al. (2013).

equilibrium appropriation levels are

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

where $A \equiv \left(36 + \delta^2\right)^{1/2}$.

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

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

$$\begin{aligned} e_i^{R,IN} &= \frac{\theta\left[(G-6)^2 + 4\delta(43 + G - d(37 + 2G)) - \delta^2(3d - 5)(11d - 9)\right]}{784\delta} \quad and \\ x_i^{R,IN} &= \frac{\theta\,[(3d - 5)\delta + G - 6]\,[18 - 3G + \delta(G - 5\delta - 98g - 61)]}{2744\delta^2} \end{aligned}$$

where $G \equiv \left[\delta\left(\delta(5 - 3d)^2 + 48d - 24\right) + 36\right]^{1/2}$.

Similar to Lemma 2, equilibrium appropriation in both periods increases in the abundance of the stock, θ, but now decreases in the biodiversity loss, d. (Equilibrium results in the special case of $d = 0$ are reported in the proof of Lemma 3.)

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

$$\begin{aligned} e_i^{B,IN} &= \frac{\theta\,[6(6 - A) + \delta\,(2 + d\,(4 + \delta - A))]}{8\delta} \quad and \\ x_i^{B,IN} &= \frac{\theta(6 + \delta - A)\,[6(A - 6) + \delta\,(2 + 4g + d\,(A - 4 - \delta))]}{16\delta^2} \end{aligned}$$

where $e_i^{B,IN}$ *(*$x_i^{B,IN}$*) is unambiguously decreasing (increasing) in* d.

When R and AO have identical objectives ($d = 0$), first-period equilibrium appropriation under B coincides with that under AO, $e_i^{B,IN} = e_i^{AO,IN}$, and so does that in the second period, $x_i^{B,IN} = x_i^{AO,IN}$. This result is analogous to that under flexible policy, since the R anticipates the AO's decisions, which induce socially optimal appropriation levels, making the role of the R unnecessary. However, when the R considers environmental damages, $d > 0$, he seeks to induce a lower first-period appropriation level than the AO, $e_i^{B,IN} < e_i^{AO,IN}$, since $e_i^{B,IN}$ is unambiguously decreasing in d; but a larger second-period appropriation, $x_i^{B,IN} > x_i^{AO,IN}$, since $x_i^{B,IN}$ is unambiguously increasing in d.

To understand the above results, recall that when $d = 0$, the R seeks to induce the same aggregate appropriation as the AO, implying that, in a real-life setting, the R would assign the same total allowable catch (TAC) than the sum of individual quotas that the AO would assign to its members. This holds both under flexible and inflexible policy regimes since R and AO have similar objectives.

When $d > 0$, however, the R seeks to induce a lower aggregate appropriation than the AO. In this case, the AO receives a lower TAC than the sum of individual quotas that it wanted to induce, implying that the AO evenly divides the TAC among its members, since all fishermen are cost symmetric.

Appendix 2 examines, for completeness, how our results are affected if the R remains inflexible but the AO becomes flexible, referring to this setting as "partially inflexible" (PIN). The results of Lemma 2 (Proposition 2) are unaffected when only R (AO) is present. The outcomes in Lemma 4, however, change when B is present, since first-period appropriation satisfies $e_i^{B,PIN} > e_i^{B,IN}$ for all parameters while second-period appropriation satisfies $x_i^{B,PIN} < x_i^{B,IN}$ for sufficiently severe damages.

6 Regulatory inefficiencies

In this section, we measure: (i) welfare levels in each regulatory regime (flexible and inflexible) and with each agency (R, AO, or B); (ii) the welfare losses from operating under an inflexible policy regime; and (iii) the appropriation inefficiencies, relative to the first best level, in each period.

In the absence of biodiversity losses, $d = 0$, welfare is given by equation (9) for every regulatory agency $k = \{AO, R, B\}$, both under flexible and inflexible regimes. When biodiversity losses are present, $d > 0$, welfare for AO and B still coincides with equation (9), but that of R is represented by equation (10). Welfare expressions are intractable, not allowing for comparative statics, and the next subsections rely on numerical simulations.

6.1 Welfare comparisons

Table I shows that, under flexible policy, aggregate welfare across periods is the largest under R, which coincides with B, followed by AO, and followed by NR (which is negative for all $d > 0$).[14]

			Flexible regime			Inflexible regime		
		W^{NR}	$W^{R,F}$	$W^{AO,F}$	$W^{B,F}$	$W^{R,IN}$	$W^{AO,IN}$	$W^{B,IN}$
$d=0$	$g=0$	0.2287	0.3907	0.3907	0.3907	0.3769	0.3895	0.3895
	$g=0.1$	0.2615	0.4157	0.4157	0.4157	0.3997	0.4144	0.4144
	$g=0.3$	0.3182	0.4657	0.4657	0.4657	0.4453	0.4641	0.4641
$d=0.25$	$g=0$	-0.0244	0.2335	0.2187	0.2335	0.2213	0.2240	0.2330
	$g=0.1$	-0.0082	0.2475	0.2312	0.2475	0.2343	0.2374	0.2464
	$g=0.3$	0.0152	0.2756	0.2562	0.2756	0.2602	0.2641	0.2731
$d=0.5$	$g=0$	-0.2775	0.1103	0.0469	0.1103	0.1023	0.0581	0.0611
	$g=0.1$	-0.2780	0.1166	0.0469	0.1166	0.1082	0.0604	0.0633
	$g=0.3$	-0.2880	0.1291	0.0469	0.1291	0.1199	0.0642	0.0668
$d=0.75$	$g=0$	-0.5305	0.0294	-0.1250	0.0294	0.0265	-0.1070	-0.1264
	$g=0.1$	-0.5477	0.0310	-0.1375	0.0310	0.0280	-0.1176	-0.1360
	$g=0.3$	-0.5910	0.0341	-0.1625	0.0341	0.0310	-0.1357	-0.1551

Table I. Aggregate welfare from different regulatory agencies and regimes.

A similar finding arises under inflexible policy. However, in this context, AO and B generate the highest aggregate welfare when $d = 0$, which goes in line with our results about output inefficiencies in Corollary 3(i) and 4(i) below, where these regulatory agencies generate the same and lowest inefficiencies. While all regulatory agencies exhibit the same objective function in this setting, the AO has more available tools than the R does (i.e., quotas for each fishermen, as opposed to aggregate quota). When $d = 0.25$, B yields the highest aggregate welfare; otherwise, R gives rise to the highest aggregate welfare, which supports the results in Corollary 3(iv) and 4(iii) below. Hence, R should be left alone in the commons when biodiversity loss is sufficiently severe, i.e., $d \geq 0.5$.[15]

6.2 Welfare losses from inflexible regulation

Under regulatory setting $k = \{R, AO, B\}$, the first-period welfare loss from inflexible policy is $WL_1^k \equiv W_1^{k,F} - W_1^{k,IN}$, where $W_1^{k,F}$ ($W_1^{k,IN}$) denotes the first-period equilibrium welfare when firms face a flexible (inflexible) policy. A similar definition applies to the second-period welfare loss from inflexible policy, $WL_2^k \equiv W_2^{k,F} - W_2^{k,IN}$.

[14] For presentation purposes, Table I considers $\theta = \delta = 1$.

[15] In particular, $W^{R,IN} > W^{AO,IN}$ for all $d > 0.2735$ when $g = 0$, for all $d > 0.2740$ when $g = 0.1$, and for all $d > 0.2750$ when $g = 0.3$. Similarly, $W^{R,IN} > W^{B,IN}$ for all $d > 0.3312$ when $g = 0$, for all $d > 0.3250$ when $g = 0.1$, and for all $d > 0.3164$ when $g = 0.3$. Hence, R yields a higher welfare than both AO and B when $d > 0.3312$, which holds for all values of g.

Table II considers the same parameter values as in Table I. Positive entries on the table indicate that moving from a flexible to inflexible policy regime entail a welfare loss in that period, while negative entries represent a welfare gain. For instance, when the R is alone, inflexible policy induces an increase in first-period appropriations relative to the flexible regime, producing a welfare gain in that period, $WL_1^R < 0$; but a decrease in second-period appropriations, yielding a welfare loss in that period, $WL_2^R > 0$. When environmental damages become more severe (higher d), both welfare gains and losses shrink in absolute value, making less relevant the policy regime.

		First-period welfare loss			Second-period welfare loss		
		WL_1^R	WL_1^{AO}	WL_1^B	WL_2^R	WL_2^{AO}	WL_2^B
$d = 0$	$g = 0$	-0.0026	-0.0002	-0.0002	0.0164	0.0013	0.0013
	$g = 0.1$	-0.0026	-0.0002	-0.0002	0.0186	0.0015	0.0015
	$g = 0.3$	-0.0026	-0.0002	-0.0002	0.0229	0.0018	0.0018
$d = 0.25$	$g = 0$	-0.0008	7.3×10^{-7}	-0.0005	0.0129	-0.0053	0.0053
	$g = 0.1$	-0.0008	7.3×10^{-7}	-0.0005	0.0140	-0.0061	0.0060
	$g = 0.3$	-0.0008	7.3×10^{-7}	-0.0005	0.0161	-0.0079	0.0074
$d = 0.5$	$g = 0$	-0.0001	0.0002	-0.0009	0.0083	-0.0118	0.0344
	$g = 0.1$	-0.0001	0.0002	-0.0009	0.0086	-0.0137	0.0388
	$g = 0.3$	-0.0001	0.0002	-0.0009	0.0094	-0.0175	0.0475
$d = 0.75$	$g = 0$	-7.9×10^{-6}	0.0004	0.0022	0.0029	-0.0184	0.0929
	$g = 0.1$	-7.9×10^{-6}	0.0004	0.0022	0.0030	-0.0213	0.1041
	$g = 0.3$	-7.9×10^{-6}	0.0004	0.0022	0.0031	-0.0272	0.1263

Table II. Welfare losses from inflexible regulation.

When the AO is alone, a similar pattern as with R emerges if environmental damages are low. However, when d increases, the AO overexploits the resource in the first period, giving rise to welfare losses relative to a flexible regime; but underexploits it in the second period, generating a welfare gain in that period. Overall, the latter dominates the former effect when damages are sufficiently high; as shown in Appendix 1 (Table A.3 reports aggregate welfare losses, $WL_1^k + WL_2^k$, for every k). When both agencies are present, B, welfare losses arise in both periods under all parameter conditions, but increase when environmental damages become more severe.[16]

We also identify the first-period welfare loss from inflexible regulation relative to the first best, $\widetilde{WL}_1^k \equiv W_1^{R,F} - W_1^{k,IN}$, since only the R internalizes both types of externalities; and similarly in the second period. Table A.5 in the appendix presents these welfare losses, showing that, relative to table II, the columns reporting WL_1^R and WL_2^R are unaffected, and the rows where $d = 0$ are also unchanged. However, when biodiversity loss is severe, the welfare loss of AO and B is larger than in table II because this loss accounts for both sources of inefficiencies (due to inflexibility and

[16] Appendix 1 evaluates our numerical results allowing for discounting, $\delta = 1/2$, showing that welfare losses under B are emphasized, but attenuated under R or AO.

ignoring biodiversity loss).

6.3 Appropriation differentials

To further examine the previous welfare comparisons, in this section we measure the difference in the appropriation level under an inflexible policy regime relative to the first-best outcome, namely, the appropriation level that the R chooses under a flexible regime (as the AO ignores environmental damages), that is,

$$FPD^k = e_i^{k,IN} - e_i^{R,F} \quad \text{and} \quad SPD^k = x_i^{R,F} - x_i^{k,IN}$$

where FPD^k (SPD^k) denotes first-period (second-period) appropriation differential. FPD^k can, alternatively, be expressed as follows

$$FPD^k = \underbrace{\left(e_i^{k,IN} - e_i^{k,F}\right)}_{\text{Diff. from inflexibility}} + \underbrace{\left(e_i^{k,F} - e_i^{R,F}\right)}_{\text{Diff. from ignoring externality}}$$

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

$$SPD^k = \left(x_i^{k,F} - x_i^{k,IN}\right) + \left(x_i^{R,F} - x_i^{k,F}\right).$$

Intuitively, FPD^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, $e_i^{k,IN} - e_i^{k,F}$; and another stemming from this agency not internalizing the environmental damage in its policies, represented in the second term, $e_i^{k,F} - e_i^{R,F}$. A similar argument applies to SPD^k. The first inefficiency is present in contexts where the R and AO have the same objective function ($d = 0$), but the second only emerges when these agencies exhibit different objectives ($d > 0$).

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

Corollary 2. *First-period equilibrium appropriation satisfies $e_i^{k,IN} > e_i^{k,F}$ under all parameter values, and for every regulatory setting $k = \{R, AO, B\}$. Second-period equilibrium appropriation satisfies $x_i^{k,F} > x_i^{k,IN}$ for $k = \{R, AO\}$ under all parameter values, but $x_i^{B,IN} > x_i^{B,F}$ for all $d > \sqrt{37} - 6 \simeq 0.08$. In addition, the second inefficiency is nil for R and B in both the first and second period since $e_i^{R,F} = e_i^{B,F}$ and $x_i^{R,F} = x_i^{B,F}$, whereas for the AO it is positive because $e_i^{AO,F} > e_i^{R,F}$ and $x_i^{AO,F} > x_i^{B,F}$.*

Therefore, every agency k produces first-period appropriation inefficiencies when operating under an inflexible regime, i.e., $e_i^{k,IN} > e_i^{k,F}$ for all k, thus overexploiting the resource relative to its first-best level (first source of inefficiency described above). This result holds even when $d = 0$, but the differential is augmented when $d > 0$ under AO. In the second period, however, the R and

AO underexploit the resource, entailing that $x_i^{R,F} > x_i^{R,IN}$ and $x_i^{AO,F} > x_i^{AO,IN}$, whereas the B overexploits it relative to the first-best level. The following corollary ranks FPDs across regulatory settings.

Corollary 3. *First-period appropriation differentials satisfy:*

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

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

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

iv $FPD^B > FPD^{AO} > FPD^R > 0$ *otherwise.*

Figure 2 depicts FPD^R, which is monotonically decreasing in d, as R internalizes the environmental externality; FPD^{AO}, which is unaffected by d since this agency ignores environmental damages; and FPD^B, which is monotonically increasing in d. This increasing pattern occurs because the AO, upon observing a more stringent aggregate quota from the R, responds relaxing individual quotas to its members, giving rise to a larger appropriation differential.[17]

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

Insert Here Figure 2: First-period appropriation differentials.

First-period inefficiencies are unaffected by the rate of growth of the resource, g. Intuitively, a higher g increases second-period profits, but does not affect fishermen's first-period incentives to marginally increase their appropriation, e_i. In other words, fishermen anticipate that increasing their first-period exploitation gives rise to a future marginal cost, facing a more depleted resource, but this marginal cost is constant in e_i.[18] Therefore, first-period appropriation is not a function of growth rate g and, hence, first-period inefficiencies are also unaffected by g.

We next rank second-period differentials in the three regulatory settings. (Cutoff $\widehat{d}$ is defined, for compactness, in the proof of Corollary 4 in the appendix.)

Corollary 4. *Second-period appropriation differentials satisfy:*

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

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

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

[18] Technically, this is due to linear separability in the second-period profit function, $\frac{\theta(1+g)-(e_i+e_j)}{9}$, i.e., the marginal effect of increasing e_i is unaffected by g.

iii $SPD^{AO} > SPD^{R} > 0 > SPD^{B}$ *otherwise.*

Corollary 4(i) embodies $d = 0$ as a special case, where $SPD^{R} > SPD^{AO} = SPD^{B}$. When d is relatively low, $0 < d < 0.08$, a similar ranking emerges, but B yields smaller differentials than AO because R (who is present in B) helps attenuate the environmental externality. When environmental damages are moderate, $0.08 \leq d < \widehat{d}$, the same ranking still applies but $SPD^{B} < 0$, as shown in Corollary 2, i.e., $x_i^{R,F} < x_i^{B,IN}$, implying that B overexploits the commons relative to its efficient level. Therefore, choosing the regulatory agency in this setting (R, AO, or B) depends on whether society seeks to avoid an underexploitation of the resource (the smallest one arising with AO) or its overexploitation with B. Finally, when environmental damages become more severe, $d \geq \widehat{d}$, society must compare the (smallest) underexploitation, which happens with R, or the overexploitation that occurs with B.

This result goes in line with that in Corollary 3, as the AO becomes more inefficient, relative to the R and B, when biodiversity losses are more severe (higher d). In other words, the R generates the largest differentials when d is relatively low, $d < \widehat{d}$, and it should not manage the resource. Otherwise the AO is the agent giving rise to the largest differentials. In terms of policy implications, the AO (B) should manage the CPR if society prefers inefficiencies originating from the underexploitation (overexploitation) of the resource and damages are relatively low, $d < \widehat{d}$; but R (B) should manage the CPR if society values underexploitation (overexploitation) and damages are relatively severe.

In addition, while cutoff $\widehat{d}$ is highly nonlinear, one can numerically show that it increases in the growth rate of the resource, g. When $g = 0.1$, for instance, this cutoff becomes $\widehat{d} = 0.809$; and when g increases to $g = 0.3$, this cutoff increases to $\widehat{d} = 0.869$. Therefore, the ranking of appropriation differentials in Corollary 4(ii) expands when the resource regenerates faster (higher g). Although the specific regulatory agency in case (ii) depends on the trade-off between under- and overexploitation described above, the R is unambiguously welfare reducing and should be avoided, opting for AO or B instead.

For illustration purposes, Table III evaluates first- and second-period differentials in each regulatory setting. First-period differentials exhibit the same patterns as in figure 2. In addition, a faster regeneration rate, g, does not affect first-period differentials, but increases the absolute value of second-period differentials. When environmental damages increase, SPD^{B} becomes more substantial, indicating a significant overexploitation with B.

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

Table III. First- and second-period differentials.

7 Discussion

Inefficiencies under a flexible policy. Our paper shows that, when fishermen face a flexible regulatory setting, where quotas can be quickly adjusted across periods, socially optimal appropriation levels arise under R or B (first best), but socially excessive appropriation emerges under AO; as summarized in the top row of table IV. This inefficiency does not originate from the policy's flexibility, of course, but from the AO ignoring biodiversity losses ($d > 0$). When third-party externalities are absent (left column of the table), all regulatory agencies yield first-best outcomes under a flexible policy regime. Relative to no regulation, this policy 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.

	$d = 0$	$d > 0$
Flexible policy	No inefficiencies from any agency k	Inefficiency only with AO
Inflexible policy	Same inefficiency from every agency k	Inefficiencies may be lower for R

Table IV. Summary of inefficiencies

Inefficiencies under an inflexible policy. 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; as summarized at the bottom row of table IV. 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 findings suggest that policies should be revisited every period, as expected, but especially when only the R is active, as this agent generates the largest inefficiencies when biodiversity losses are minor. This is the case in several countries, such as Vietnam, Indonesia, or Sri Lanka, where policies are rarely revised. Similarly, our findings entail that R should manage the resource when it regenerates fast (such as anchovies and Yellowtail flounder), but its regulatory inefficiencies are more substantial when the CPR regenerates slowly (such as mollusks or American plaice).

Overlapping regulations. When R and AO exhibit the same objectives ($d = 0$), a cooperative can efficiently organize the use of the CPR, suggesting that the R can, essentially, step back, allowing the AO to become the only regulating agency in the resource, determining quotas and fines among its members. Our results are, however, affected when the AO and R exhibit different objectives ($d > 0$), since we find that all agencies generate inefficiencies. Specifically, when biodiversity losses are relatively low, the R generates the most inefficiencies, both in the first and second periods, and it should not manage the resource. In this case, the AO (B) should regulate the CPR if society prefers that inefficiencies originate from the underexploitation (overexploitation) of the resource, respectively. However, when biodiversity loss is severe, the AO gives rise to the most inefficiencies, calling for the R to manage the CPR. This result is emphasized when the resource regenerates faster, since the third-party externality becomes more severe, and the inefficiencies from AO are larger, ultimately making the R socially preferable under more settings.

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. Fourth, an extension could consider cost-asymmetric fishermen. In the absence of regulation, the fisherman benefiting from a cost advantage would appropriate more intensively than its rival. Regulation internalizes such cost advantage, potentially inducing more appropriation from the most efficient fisherman. Fifth, if environmental damages are convex in aggregate appropriation, we should expect more stringent regulations under R and B, yielding larger differences with respect to AO. However, regulatory inefficiencies may be affected. Sixth, if market power enters into our welfare analysis, a cartel could potentially affect our welfare rankings. Finally, one could allow for the possibility of imperfect monitoring in flexible or inflexible regulation and examine how our results are affected.

8 Appendix

8.1 Appendix 1 - Welfare levels

Table A.1 reports first- and second-period welfare levels without regulation, NR, with flexible regulation when only R is present, when only AO is active, and when B operate, respectively, considering the same parameter values as in Tables I-III in the main body of the paper and no discounting.

Table A.1 shows that, when $d = 0$, flexible policy is welfare reducing (enhancing) in the first (second) period, relative to NR, yielding nonetheless an overall increase in welfare. When $d > 0$, however, flexible policy is welfare improving in both periods and for every regulatory agency (R, AO, and B).

		First-period welfare				Second-period welfare			
		W_1^{NR}	$W_1^{R,F}$	$W_1^{AO,F}$	$W_1^{B,F}$	W_2^{NR}	$W_2^{R,F}$	$W_2^{AO,F}$	$W_2^{B,F}$
$d = 0$	$g = 0$	0.2414	0.2344	0.2344	0.2344	−0.0127	0.1563	0.1563	0.1563
	$g = 0.1$	0.2414	0.2344	0.2344	0.2344	0.0201	0.1813	0.1813	0.1813
	$g = 0.3$	0.2414	0.2344	0.2344	0.2344	0.0768	0.2313	0.2313	0.2313
$d = 0.25$	$g = 0$	0.0933	0.1357	0.1406	0.1357	−0.1177	0.0978	0.0781	0.0978
	$g = 0.1$	0.0933	0.1357	0.1406	0.1357	−0.1015	0.1118	0.0906	0.1118
	$g = 0.3$	0.0933	0.1357	0.1406	0.1357	−0.0781	0.1399	0.1156	0.1399
$d = 0.5$	$g = 0$	−0.0549	0.0615	0.0469	0.0615	−0.2226	0.0488	0	0.0488
	$g = 0.1$	−0.0549	0.0615	0.0469	0.0615	−0.2231	0.0551	0	0.0551
	$g = 0.3$	−0.0549	0.0615	0.0469	0.0615	−0.2331	0.0676	0	0.0676
$d = 0.75$	$g = 0$	−0.2030	0.0156	−0.0469	0.0156	−0.3275	0.0138	−0.0781	0.0138
	$g = 0.1$	−0.2030	0.0156	−0.0469	0.0156	−0.3447	0.0154	−0.0906	0.0154
	$g = 0.3$	−0.2030	0.0156	−0.0469	0.0156	−0.3880	0.0185	−0.1156	0.0185

Table A.1. Welfare levels in equilibrium under flexible policy, $\delta = 1$.

Table A.2 provides first- and second-period welfare levels, as in Table A.1, but considering an inflexible policy regime.

		First-period welfare				Second-period welfare			
		W_1^{NR}	$W_1^{R,IN}$	$W_1^{AO,IN}$	$W_1^{B,IN}$	W_2^{NR}	$W_2^{R,IN}$	$W_2^{AO,IN}$	$W_2^{B,IN}$
$d = 0$	$g = 0$	0.2414	0.2370	0.2346	0.2346	−0.0127	0.1399	0.1549	0.1549
	$g = 0.1$	0.2414	0.2370	0.2346	0.2346	0.0201	0.1627	0.1798	0.1798
	$g = 0.3$	0.2414	0.2370	0.2346	0.2346	0.0768	0.2083	0.2295	0.2295
$d = 0.25$	$g = 0$	0.0933	0.1364	0.1406	0.1406	−0.1177	0.0849	0.0834	0.0924
	$g = 0.1$	0.0933	0.1364	0.1406	0.1406	−0.1015	0.0979	0.0968	0.1058
	$g = 0.3$	0.0933	0.1364	0.1406	0.1406	−0.0781	0.1238	0.1235	0.1325
$d = 0.5$	$g = 0$	−0.0549	0.0617	0.0467	0.0467	−0.2226	0.0406	0.0118	0.0144
	$g = 0.1$	−0.0549	0.0617	0.0467	0.0467	−0.2231	0.0465	0.0137	0.0166
	$g = 0.3$	−0.0549	0.0617	0.0467	0.0467	−0.2331	0.0582	0.0175	0.0201
$d = 0.75$	$g = 0$	−0.2030	0.0156	−0.0473	−0.0473	−0.3275	0.0109	−0.0597	−0.0791
	$g = 0.1$	−0.2030	0.0156	−0.0473	−0.0473	−0.3447	0.0124	−0.0693	−0.0887
	$g = 0.3$	−0.2030	0.0156	−0.0473	−0.0473	−0.3880	0.0154	−0.0884	−0.1078

Table A.2. Welfare levels in equilibrium under inflexible policy, $\delta = 1$.

Table A.3 reports the aggregate welfare loss from Table II, $WL^k = WL_1^k + WL_2^k$ for every k.

		Aggregate welfare loss		
		WL^R	WL^{AO}	WL^B
$d = 0$	$g = 0$	0.0138	0.0011	0.0011
	$g = 0.1$	0.0160	0.0013	0.0013
	$g = 0.3$	0.203	0.0016	0.0016
$d = 0.25$	$g = 0$	0.0121	−0.0053	0.0048
	$g = 0.1$	0.0132	−0.0061	0.0055
	$g = 0.3$	0.0153	−0.0079	0.0069
$d = 0.5$	$g = 0$	0.0082	−0.0116	0.0335
	$g = 0.1$	0.0085	−0.0135	0.0379
	$g = 0.3$	0.0093	−0.0173	0.0466
$d = 0.75$	$g = 0$	0.0029	−0.0180	0.0951
	$g = 0.1$	0.0030	−0.0209	0.1063
	$g = 0.3$	0.0031	−0.0268	0.1285

Table A.3. Aggregate welfare losses.

Table A.4 evaluates welfare losses in the first and second period, being analogous to table I in the main body of the paper, but considering that $\delta = 1/2$.

		First-period welfare loss			Second-period welfare loss		
		WL_1^R	WL_1^{AO}	WL_1^B	WL_2^R	WL_2^{AO}	WL_2^B
$d = 0$	$g = 0$	-0.0002	-0.00001	-0.00001	0.0032	0.0003	0.0002
	$g = 0.1$	-0.0002	-0.00001	-0.00001	0.0037	0.0003	0.0003
	$g = 0.3$	-0.0002	-0.00001	-0.00001	0.0047	0.0004	0.0004
$d = 0.25$	$g = 0$	-0.0001	0.00001	-0.0002	0.0057	-0.0027	0.0075
	$g = 0.1$	-0.0001	0.00001	-0.0002	0.0059	-0.0031	0.0086
	$g = 0.3$	-0.0001	0.00001	-0.0002	0.0063	-0.0041	0.0108
$d = 0.5$	$g = 0$	-9.7×10^{-6}	0.00004	-0.0002	0.0052	-0.0056	0.0404
	$g = 0.1$	-9.7×10^{-6}	0.00004	-0.0002	0.0051	-0.0066	0.0456
	$g = 0.3$	-9.7×10^{-6}	0.00004	-0.0002	0.0051	-0.0086	0.0561
$d = 0.75$	$g = 0$	-6.2×10^{-7}	0.00007	0.00074	0.0022	-0.0085	0.1068
	$g = 0.1$	-6.2×10^{-7}	0.00007	0.00074	0.0021	-0.0101	0.1194
	$g = 0.3$	-6.2×10^{-7}	0.00007	0.00074	0.0020	-0.0131	0.1445

Table A.4. Welfare losses considering $\delta = 1/2$.

Table A.5 evaluates welfare losses from inflexible regulation relative to the first-best outcome.

		First-period welfare loss			Second-period welfare loss		
		$\widetilde{WL}_1^R$	$\widetilde{WL}_1^{AO}$	$\widetilde{WL}_1^B$	$\widetilde{WL}_2^R$	$\widetilde{WL}_2^{AO}$	$\widetilde{WL}_2^B$
$d = 0$	$g = 0$	-0.0026	-0.0002	-0.0002	0.0164	0.0013	0.0013
	$g = 0.1$	-0.0026	-0.0002	-0.0002	0.0186	0.0015	0.0015
	$g = 0.3$	-0.0026	-0.0002	-0.0002	0.0229	0.0018	0.0018
$d = 0.25$	$g = 0$	-0.0008	-0.0049	-0.0049	0.0129	0.0144	0.0054
	$g = 0.1$	-0.0008	-0.0049	-0.0049	0.0140	0.0150	0.0060
	$g = 0.3$	-0.0008	-0.0049	-0.0049	0.0161	0.0164	0.0074
$d = 0.5$	$g = 0$	-0.0001	0.0148	0.0148	0.0083	0.0370	0.0344
	$g = 0.1$	-0.0001	0.0148	0.0148	0.0086	0.0414	0.0385
	$g = 0.3$	-0.0001	0.0148	0.0148	0.0094	0.0501	0.0475
$d = 0.75$	$g = 0$	-7.9×10^{-6}	0.0629	0.0629	0.0029	0.0735	0.0929
	$g = 0.1$	-7.9×10^{-6}	0.0629	0.0629	0.0030	0.0847	0.1041
	$g = 0.3$	-7.9×10^{-6}	0.0629	0.0629	0.0031	0.1069	0.1263

Table A.5. Welfare losses relative to the first best and $\delta = 1$.

8.2 Appendix 2 - Partially inflexible policy

We next examine how our results are affected if the R remains inflexible but the AO becomes flexible, referring to this setting as "partially inflexible" (PIN). When only R is present, his behavior coincides with that in Lemma 2, given his inflexibility; when only AO is active, its behavior coincides with that in Proposition 2 because of its flexibility. When both regulatory agencies are present (B), however, our results are affected, as shown in Lemma A1.

Lemma A1. *When both AO and R are present under a partially inflexible policy, first- and second-period equilibrium appropriation levels are*

$$e_i^{B,PIN} = \frac{\theta\left[4 - \delta - 2d(2-\delta)\right]}{16} \quad \text{and} \quad x_i^{B,PIN} = \frac{\theta\left[4 + 8g + \delta + 2d(2-\delta)\right]}{32}$$

where $e_i^{B,PIN}$ ($x_i^{B,PIN}$) is unambiguously decreasing (increasing) in d. Relative to inflexible policy (Lemma 4), first-period appropriation satisfies $e_i^{B,PIN} > e_i^{B,IN}$ for all admissible parameters and $e_i^{B,PIN} - e_i^{B,IN}$ is increasing in d; and second-period appropriation satisfies $x_i^{B,PIN} < x_i^{B,IN}$ for all $d > d_{PIN}$, where $d_{PIN} \equiv \frac{2(\theta-6)(A-6)+\delta^3\theta-2\delta(\theta+2+4g)+4\theta\delta^2(1+2g)}{2\delta[A-4-\delta(\theta(2-\delta)+1)]}$.

In the inflexible regime of Lemma 4, the R anticipates that the AO cannot revise second-period fines to correct for a socially excessive first-period appropriation. Under the partially inflexible regime of Lemma A1, however, the AO can use second-period fines to correct for first-period inefficiencies, implying that the R can induce more generous first-period appropriation levels when the AO is flexible than otherwise, $e_i^{B,PIN} > e_i^{B,IN}$. This ranking holds even when third-party externalities are absent ($d = 0$), since it originates from the R benefiting from the AO's ability to revise its second-period policy; and the ranking is emphasized when biodiversity losses become more severe, $d > 0$. In addition, appropriation is socially excessive since $e_i^{B,PIN} > e_i^{R,F}$, where $e_i^{R,F}$ denotes the exploitation that the R induces under a flexible policy regime, as identified in Proposition 2. Since the R considers both cost-related and third-party externalities, this exploitation level is socially optimal.

8.3 *Proof of Lemma 1*

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

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

Differentiating with respect to x_i, yields

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

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

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

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

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

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

8.4 *Proof of Proposition 1*

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

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

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

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

Therefore, every fisherman i solves

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

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

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

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

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

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

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

which is positive for all parameter values.

8.5 *Proof of Proposition 2*

8.5.1 Only AO is present

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

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

Differentiating with respect to x_i, yields

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

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

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

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

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

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

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

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

which simplifies to

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

Differentiating with respect to x_i, yields

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

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

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

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

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

which, solving for t_i and t_j, yields the fine that induces fishermen i and j to appropriate exactly x_i^{SO} and x_j^{SO}, that is, $t_i^{AO} = t_j^{AO} = \frac{1}{4\alpha}$, which is positive for all α values.

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

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

Differentiating with respect to e_i, yields

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

Solving for e_i, we obtain a best response function

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

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

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

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

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

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

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

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

Differentiating with respect to e_i, yields

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

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

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

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

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

which, solving for f_i, yields

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

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

8.5.2 Only R is present

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

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

Differentiating with respect to x_i, yields

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

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

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

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

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

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

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

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

Differentiating with respect to x_i, yields

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

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

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

Setting it equal to the equilibrium second-period appropriation found above, $x_i^R(E)$, we find

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

which is positive for all β and d values.

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

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

Differentiating with respect to e_i, yields

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

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

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

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

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

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

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

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

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

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

$$e_i^{R,F}=\frac{\theta(1-d)(4-\delta\left(1-d\right))}{16}$$

which satisfies $\frac{\partial e_i^{R,F}}{\partial d}=-\frac{\theta}{8}[2+\delta(d-1)]$, which is negative for all admissible parameters.

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

$$F^R=\frac{4+\delta+d\left[12-\delta(6-5d)\right]}{8\beta}$$

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

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

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

which satisfies $\frac{\partial x_i^{R,F}}{\partial d}=-\frac{\theta}{32}[8(d+g)+3\delta(d-1)^2]$, which is negative for all admissible parameters.

8.5.3 Both R and AO are present

Sixth stage. Fisherman i's maximization problem is

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

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

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

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

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

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

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

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

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

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

Differentiating with respect to x_i, yields

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

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

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

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

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

which is positive for all α values.

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

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

Differentiating with respect to x_i, yields

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

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

$$x_i^{B,F} = \frac{(1-d)\,[\theta(1+g) - E]}{4}.$$

Setting it equal to the equilibrium second-period appropriation found above, $x_i^{B,F}$, we obtain $T^B = \frac{d}{\beta}$, which implies that the fine induces compliance. Hence, fine $t_i^B = \frac{1+\beta T}{4\alpha}$ evaluated at $T^B = \frac{d}{\beta}$ becomes $t_i^B = \frac{1+d}{4\alpha}$.

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

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

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

Differentiating with respect to e_i, yields

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

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

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

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

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

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

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

Differentiating with respect to e_i, yields

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

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

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

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

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

which is positive for all parameter values.

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

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

Differentiating with respect to e_i, yields

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

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

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

which coincides with that when only R is present. Setting it equal to the equilibrium first-period appropriation found above, e_i^B, we obtain

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

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

Inserting these results into second-period appropriation, $x_i^B(E)$, we find that

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

which coincides with that when only R is present.

Comparison. It is easy to show that, when only AO operates, $e_i^{AO} > x_i^{AO}$ if and only if

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

which simplifies to $g < \frac{4-3\delta}{8}$, which holds by definition. Similarly, $e_i^k > x_i^k$ holds for $k = \{R, B\}$ if and only if

$$\frac{\theta(1-d)\left[4-\delta(1-d)\right]}{16} > \frac{\theta(1-d)\left[4+8g+\delta+d(4-\delta(2-d))\right]}{32}$$

which simplifies to $g < \frac{[4+\delta(d-3)](1-d)}{8} \equiv \overline{g}(d)$, where cutoff $\overline{g}(d)$ unambiguously decreases in both d and δ. Therefore, $\overline{g}(1) < \overline{g}(0)$, implying that if condition $g < \frac{4-3\delta}{8} = \overline{g}(0)$ holds, condition $g < \overline{g}(d)$ also holds for all admissible values of d. Hence, first-period equilibrium appropriation exceeds second-period appropriation for every regulatory setting k, $e_i^k > x_i^k$.

8.6 *Proof of Corollary 1*

Evaluating the results in Proposition 2 when only the R is present at $d = 0$, we obtain $e_i^{R,F} = \frac{\theta(4-\delta)}{16}$, $x_i^{R,F} = \frac{\theta(4+8g+\delta)}{32}$, and $F^R = \frac{4+\delta}{8\beta}$. Similarly, evaluating the results under B at $d = 0$, we find that

$$e_i^{B,F} = \frac{\theta(4-\delta)}{16}, \;\; x_i^{B,F} = \frac{\theta(4+8g+\delta)}{32}, \;\; F^B = T^B = 0, \;\; f_i^B = \frac{4+\delta}{16\alpha} \;\; \text{and} \;\; t_i^B = \frac{1}{4\alpha}.$$

Finally, equilibrium results under AO are unaffected by d, thus coinciding with those in Proposition 2.

8.7 *Proof of Lemma 2*

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

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

Differentiating with respect to x_i, yields

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

Solving for x_i, we obtain a best response function

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

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

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

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

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

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

Differentiating with respect to e_i, yields

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

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

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

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

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

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

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

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

which simplifies to

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

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

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

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

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

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

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

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

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

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

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

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

8.8 *Proof of Lemma 3*

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

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

Differentiating with respect to x_i, yields

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

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

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

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

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

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

Second stage. Fisherman i anticipates 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 and solving for e_i, we obtain a best response function

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

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

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

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

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

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

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

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

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

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

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

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

where $G \equiv \left[\delta\left(\delta(5-3d)^2+48d-24\right)+36\right]^{1/2}$. Evaluating first-period appropriation at fine $F^{R,IN}$, we obtain

$$e_i^{R,IN} = \frac{\theta\left[(G-6)^2+4\delta(43+G-d(37+2G))-\delta^2(3d-5)(11d-9)\right]}{784\delta}$$

Fine $F^{R,IN}$ is positive for all β values, increasing in d, and the second-period appropriation in equilibrium is

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

Differentiating $e_i^{R,IN}$ with respect to d, we obtain

$$\frac{\partial e_i^{R,IN}}{\partial d} = -\frac{\theta\left[144+25G-13\delta(9-5\delta+G)+3d\delta(57+3\delta(4d-11)+4G)\right]}{196G}$$

which is negative for all admissible values of θ, d, and δ.

When $d=0$, the above results become

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

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

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

Then, evaluating second-period equilibrium appropriation, $x_i^{R,IN}$, at penalty $F^{R,IN}$, yields

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

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

8.9 *Proof of Lemma 4*

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

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

Differentiating with respect to x_i, we obtain

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

where $A \equiv \left(36 + \delta^2\right)^{1/2}$, and satisfies $\frac{\partial e^{B,IN}}{\partial d} = \frac{\theta(4 + \delta - A)}{8}$, which is negative for all values of δ, entailing that $e^{B,IN}$ is unambiguously decreasing in d.

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

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

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

$$e_i^{B,IN} = \frac{\theta(36-6A+2\delta)}{8\delta}, \text{ and } x_i^{B,IN} = \frac{\theta(6+\delta-A)\left[\delta\left(1+2g\right)+3(A-6)\right]}{8\delta^2}.$$

8.10 *Proof of Lemma A1*

Fifth stage. In this stage, every fisherman i takes the second-period fines from the AO as given, t_i and t_j, and the fine from the R as given, F (which he sets in the first period and cannot revise). Therefore, every fisherman i faces the same second-period maximization problem as in the fourth stage of Lemma 4, yielding an equilibrium extraction $x_i(f_i, f_j, F) = \frac{[\theta(1+g)-E](2-2\alpha(2f_i-f_j)-\beta F)}{6}$, where $E \equiv e_i + e_j$.

Fourth stage. The AO seeks to induce the second-period appropriation levels, x_i and x_j, that maximize its objective function. Its maximization problem coincides with that in Proposition 2, particularly under B (fifth stage in that context), and evaluated at a fine from the R of $T = F$ since in our current setting the R only chooses its policy at the beginning of the game. Specifically, the AO seeks to induce $x_i^* = \frac{[\theta(1+g)-E](1-\beta T)}{4}$.

Third stage. Every fisherman i anticipates second-period profits of $\pi^{2nd}(x_i^*, x_j^*) = x_i^* - \frac{x_i^*(x_i^*+x_j^*)}{\theta(1+g)-E}$, which yields $\pi^{2nd}(x_i^*, x_j^*) = \frac{[\theta(1+g)-E](1-\beta^2F^2)}{9}$. Therefore, fisherman i chooses the first-period appropriation, e_i, that solves

$$\max_{e_i \geq 0} \ \pi_i^{1st}(e_i, e_j) + \delta\pi_i^{2nd}(x_i^*, x_j^*)$$

where $\pi_i^{1st}(e_i, e_j) = e_i - \frac{e_i(e_i+e_j)}{\theta} - \alpha f_i\left(e_i - \overline{e}_i\right) - \frac{\beta F}{2}(e_i + e_j - \widehat{e})$ denotes first-period profits, and $\pi_i^{2nd}(x_i^*, x_j^*)$ was found above. Differentiating with respect to e_i and solving for e_i, yields the best response function

$$e_i(e_j) = \frac{\theta\left[8\left(1-f_i\alpha\right)-\delta-F\beta(4-F\beta\delta)\right]}{16} - \frac{1}{2}e_j$$

and a symmetric best response function arises for fisherman $j \neq i$. Simultaneously solving for e_i and e_j, we obtain

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

Second stage. In this stage, the AO seeks to induce the first-period appropriation levels, e_i and e_j, that maximize its objective function. That is,

$$\max_{e_i, e_j \geq 0} \ \left[\pi_i^{1st}(e_i, e_j) + \delta\pi_i^{2nd}(x_i^*, x_j^*)\right] + \left[\pi_j^{1st}(e_i, e_j) + \delta\pi_j^{2nd}(x_i^*, x_j^*)\right]$$

where the AO anticipates the second-period profits that each fisherman will earn in the second period, as shown above. Differentiating with respect to e_i and e_j, and simultaneously solving for e_i and e_j, yields $e_i^* = \frac{\theta[4-\delta(1+F\beta)](1-F\beta)}{16}$. To induce this appropriation level, the AO sets a first-period fine pair (f_i, f_j) such that $\frac{\theta[8+8\alpha(f_j-2f_i)-\delta-F\beta(4-F\beta\delta)]}{24} = \frac{\theta[4-\delta(1+F\beta)](1-F\beta)}{16}$ for both i and j, which yields $f_i = f_j = \frac{4+\delta+F\beta(4-\delta F\beta)}{16\alpha}$.

First stage. In this stage, the R seeks to induce the first-period appropriation levels, e_i and e_j, that maximize total welfare, that is,

$$\max_{e_i,e_j\geq 0} \left[\pi_i^{1st}(e_i,e_j) + \delta\pi_i^{2nd}(x_i^*,x_j^*)\right] + \left[\pi_j^{1st}(e_i,e_j) + \delta\pi_j^{2nd}(x_i^*,x_j^*)\right] - d\left(e_i + e_j + \delta\left(x_i^* + x_j^*\right)\right)$$

which is evaluated at the equilibrium second-period appropriation levels, x_i^* and x_i^*, found in the fourth stage. Differentiating with respect to e_i and e_j, and simultaneously solving for e_i and e_j, yields $e_i^{**} = \frac{\theta[4(1-d-F\beta)-\delta(1-2d+F\beta)(1-F\beta)]}{16}$. To induce this appropriation level, the R sets a first-period fine F such that $\frac{\theta[4(1-d-F\beta)-\delta(1-2d+F\beta)(1-F\beta)]}{16} = \frac{\theta[4-\delta(1+F\beta)](1-F\beta)}{16}$, which yields $F = \frac{\delta-2}{F\beta}$, which is negative since $\delta \in [0,1]$, entailing that $F^{B,PIN} = 0$ in this context. As a consequence, the first-period equilibrium appropriation becomes $e_i^{B,PIN} = \frac{\theta[4-\delta-2d(2-\delta)]}{16}$ and a second-period equilibrium appropriation of $x_i^{B,PIN} = \frac{\theta[4+8g+\delta+2d(2-\delta)]}{32}$.

Comparisons. Comparing $e^{B,PIN}$ against $e^{B,IN}$ from Lemma 4, we obtain that the difference $e_i^{B,PIN} - e_i^{B,IN} = \frac{\theta\left[12A-72-\delta^2+2d\delta(A-6)\right]}{16\delta}$, , where $A \equiv \left(36+\delta^2\right)^{1/2}$ as defined in Lemma 2. This difference is positive for all $d > \frac{72+\delta^2-12A}{2\delta(A-6)}$. However, cutoff $\frac{72+\delta^2-12A}{2\delta(A-6)}$ is negative because its numerator (denominator) is unambiguously negative (positive). Therefore, condition $e_i^{B,PIN} > e_i^{B,IN}$ holds for all admissible values of $d \geq 0$. In addition, the the difference $e_i^{B,PIN} - e_i^{B,IN}$ satisfies $\frac{\partial\left(e_i^{B,PIN}-e_i^{B,IN}\right)}{\partial d} = \frac{\theta(A-6)}{8} > 0$ for all admissible parameters. Comparing now $x_i^{B,PIN}$ against $x_i^{B,IN}$ from Lemma 4, we obtain that $x_i^{B,PIN} < x_i^{B,IN}$ for all $d > \frac{2(\theta-6)(A-6)+\delta^3\theta-2\delta(\theta+2+4g)+4\theta\delta^2(1+2g)}{2\delta[A-4-\delta(\theta(2-\delta)+1)]} \equiv d_{PIN}$.

8.11 *Proof of Corollary 2*

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

$$\begin{aligned} FPD^R &= e_i^{R,IN} - e_i^{R,F} \\ &= \frac{\theta\left[(G-6)^2 + 4\delta(43+G-d(37+2G)) - \delta^2(3d-5)(11d-9)\right]}{784\delta} - \frac{\theta(1-d)(4-\delta(1-d))}{16} \end{aligned}$$

which, in the case that $\delta = 1$, simplifies to

$$FPD^R = \frac{\theta\left[\sqrt{37+9d(2+d)} - 4(1+d)\right]^2}{784}$$

the numerator is positive for all admissible parameter values. Therefore, $e_i^{R,IN} > e_i^{R,F}$, entailing that $FPD^R > 0$. When $d = 0$, this inefficiency simplifies to $FPD^R = \frac{\theta\left(\sqrt{37}-4\right)^2}{784}$.

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

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

which is positive for all $\theta > 0$ and $\delta = 1$, since $e_i^{AO,IN} - e_i^{AO,F} = 0.62\theta$. Therefore, $e_i^{AO,IN} > e_i^{AO,F}$, which implies that $FPD^{AO} > 0$ in this regulatory setting too. This inefficiency is unaffected by d.

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

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

which is positive for all admissible values of θ and d. Therefore, $e_i^{B,IN} > e_i^{B,F}$, implying that $FPD^B > 0$. When $d = 0$, this inefficiency simplifies to $FPD^B = \frac{\theta\left(73-12\sqrt{37}\right)}{16}$.

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

$$
\begin{aligned}
SPD^R &= x_i^{R,F} - x_i^{R,IN} \\
&= \frac{\theta(1-d)(5+8g+d(2+d))}{32} - \frac{\theta(11-3d-G)(2G+98g+48)}{2744} \\
&= \frac{\theta\left[1372(1-d)(5+d(2+d)+8g)+32(G+3d-11)(24+\sqrt{37}+49g)\right]}{43904}
\end{aligned}
$$

which is positive for all admissible values of g and d, therefore, $SPD^R > 0$ and $x_i^{R,F} > x_i^{R,IN}$. When $d = 0$, this inefficiency simplifies to $SPD^R = \frac{\theta\left[1372(5+8g)+32(\sqrt{37}-11)(24+\sqrt{37}+49g)\right]}{43904}$.

When AO is present, we obtain that

$$
\begin{aligned}
SPD^{AO} &= x_i^{AO,F} - x_i^{AO,IN} \\
&= \frac{\theta(5+8g)}{32} - \frac{(7-\sqrt{37})(2g-17+3\sqrt{37})\theta}{8} \\
&= \frac{\theta\left[925-152\sqrt{37}+8g(\sqrt{37}-6)\right]}{32}
\end{aligned}
$$

which is positive for all admissible parameter values. Therefore $SPD^{AO} > 0$, which implies that $x_i^{AO,F} > x_i^{AO,IN}$.

When both AO and R are present, we obtain that

$$\begin{aligned} SPD^{B} &= x_i^{B,F} - x_i^{B,IN} \\ &= \frac{\theta(1-d)\left[5+8g+d(2+d)\right]}{32} - \frac{\theta(7-A)\left[6A-36+(2+4g+d\left(A-5\right))\right]}{16} \\ &= \frac{\theta\left[925-152\sqrt{37}+8g\left(\sqrt{37}-6\right)+d\left(141-24\sqrt{37}-d(1+d)-8g\right)\right]}{32} \end{aligned}$$

which is negative for all $d = \sqrt{37}-6 \simeq 0.08$, but positive otherwise. When $d = 0$, this inefficiency simplifies to $SPD^{B} = \frac{\theta\left[925-152\sqrt{37}+8g\left(\sqrt{37}-6\right)\right]}{32}$.

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

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

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

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

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

8.12 *Proof of Corollary 3*

Comparing FPD^{R} and FPD^{AO}, we obtain that

$$\begin{aligned} FPD^{R} - FPD^{AO} &= \frac{\theta\left[\sqrt{37+9d(2+d)}-4(1+d)\right]^2}{784} - \frac{(73-12\sqrt{37})\theta}{16} \\ &= \frac{\theta\left[\left[\sqrt{37+9d(2+d)}-4(1+d)\right]^2-49(73-12\sqrt{37})\right]}{784} \end{aligned}$$

Hence, $FPD^{R} - FPD^{AO}$ is positive if and only if $d < 0.68$ and, thus, $FPD^{R} > FPD^{AO}$.

Comparing FPD^R now against FPD^B, we find that

$$\begin{aligned}
FPD^R - FPD^B &= \frac{\theta\left[\sqrt{37+9d(2+d)}-4(1+d)\right]^2}{784} - \frac{\theta\left[73-12\sqrt{37}+d\left(12-2\sqrt{37}+d\right)\right]}{16} \\
&= \frac{\theta\left[\left[\sqrt{37+9d(2+d)}-4(1+d)\right]^2-49\left[73-12\sqrt{37}-d\left(12-2\sqrt{37}+d\right)\right]\right]}{784}
\end{aligned}$$

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

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

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

Finally, comparing $FPD^R(d)$ and $FPD^R(0)$, we obtain

$$\begin{aligned}
FPD^R(d) - FPD^R(0) &= \frac{\theta\left[\sqrt{37+9d(2+d)}-4(1+d)\right]^2}{784} - \frac{\theta\left(\sqrt{37}-4\right)^2}{784} \\
&= \frac{\theta\left[\left[\sqrt{37+9d(2+d)}-4(1+d)\right]^2-\left(\sqrt{37}-4\right)^2\right]}{784}
\end{aligned}$$

which is negative for all admissible values of d, implying that $FPD^R(0) \geq FPD^R(d)$. In contrast, $FPD^B(d) \geq FPD^B(0) = FPD^{AO}$, since

$$\begin{aligned}
FPD^B(d) - FPD^B(0) &= \frac{\theta\left[73-12\sqrt{37}+d\left(12-2\sqrt{37}+d\right)\right]}{16} - \frac{\theta(73-12\sqrt{37})}{16} \\
&= \frac{\theta d\left(12-2\sqrt{37}+d\right)}{16}
\end{aligned}$$

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

8.13 *Proof of Corollary 4*

Comparing SPD^R and SPD^B, we obtain that

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

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

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

which is weakly negative for all admissible parameter values and, thus, $SPD^{AO} \geq SPD^B$; and is zero if $d=0$ implying that $SPD^{AO} = SPD^B$. Comparing now SPD^R and SPD^{AO}, we find that

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

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

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

Comparing $SPD^R(d)$ and $SPD^R(0)$, we obtain

$$\begin{aligned} SPD^R(d) - SPD^R(0) &= \left[\frac{\theta(1372(1-d)(5+d(2+d)+8g)+32(G+3d-11)(24+\sqrt{37}+49g))}{43904}\right] \\ &\quad - \left[\frac{\theta(2744(8g+5)-32(\sqrt{37}-11)(18-2\sqrt{37}-(66+98g)))}{87808}\right] \\ &= \frac{\begin{array}{c}\theta(343(1-d)(5+d(2+d)+8g)-343(5+8g)-8(\sqrt{37}-11)(24+\sqrt{37}+49g) \\ +8(3d+G-11)(24+\sqrt{37}+49g))\end{array}}{10976} \end{aligned}$$

which is negative for all admissible parameter values and, thus, $SPD^R(d) > SPD^R(0)$. In addition, $SPD^B(d) < SPD^B(0)$, since

$$\begin{aligned} SPD^B(d) - SPD^B(0) &= \left[\frac{\theta\left[925-152\sqrt{37}+8g\left(\sqrt{37}-6\right)+d\left(141-24\sqrt{37}-d(1+d)-8g\right)\right]}{32}\right] \\ &\quad - \left[\frac{\theta(925-152\sqrt{37}+8g(\sqrt{37}-6))}{32}\right] \end{aligned}$$

which is negative if and only if $d > \widetilde{d}$, where cutoff $\widetilde{d}$ solves

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

When $d = 0$, this condition holds, entailing that $SPD^B(d) = SPD^B(0)$.

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