# Anticipatory Effects of Taxation in the Commons:
## *When do they work, and when do they fail?*

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**Abstract**

This paper considers a common-pool resource where a regulator announces a new policy curbing appropriation (usage fee). While firms respond reducing their appropriation once the fee is in effect, we identify under which conditions firms choose to increase their appropriation before the fee comes into effect. We demonstrate that this policy-induced appropriation increase is more likely when: (1) several firms compete for the resource; (2) firms sustain some market power; (3) firms impose significant cost externalities on each other; and (4) the resource is scarce. Our results, therefore, indicate that policy announcements can trigger large increases in resource exploitation before the policy comes into effect, thus offsetting their subsequent welfare-improving effects.

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# 1 Introduction

Usage fees are often suggested as a tool to curb the excessive appropriation that firms exploiting a common-pool resource choose if left unregulated. This fee can help firms internalize the cost externality that their appropriation imposes on other firms operating in the same commons, ultimately leading them to exploit the resource at the socially optimal level. While this analysis yields first-best outcomes once the policy comes into effect, it overlooks the potential anticipatory effects that the policy triggers in firms' appropriation decisions before the policy comes into effect. If firms choose to increase their resource exploitation —anticipating a loss in future payoffs once regulation comes into force— the policy becomes less effective since overall appropriation does not decrease as expected, and may even increase. If, instead, firms choose to decrease their exploitation, the policy becomes effective even before coming into force. While the empirical literature has extensively evaluated the potential increase or decrease in pollution before an environmental policy comes into effect, we examine how firms' anticipatory behavior is affected by industry characteristics.

Our model considers a polluting industry with $N$ firms exploiting a common pool resource (CPR) which does not have a close substitute; implying that the regulator cannot subsidize a clean alternative to affect the CPR exploitation.[1] Our setting allows for different types of industries as special cases. First, when firms are price takers and generate a cost externality on their rivals, our model resembles a standard CPR. Second, when firms face a downward sloping demand curve in the output market and do not generate cost externalities on each others' profits, our setting coincides with a standard Cournot model of quantity competition. Third, when firms face a downward sloping demand curve and generate cost externalities, our model includes features of the two extreme settings described above. Allowing for different types of industries helps us predict the anticipatory effects of taxation in different CPRs.

As expected, when firms exploit a CPR with large cost externalities and are price takers in the product market, our results show that firms increase their exploitation of the resource before the policy comes into effect. This setting is, however, rather stylized. When we relax the above assumptions, allowing for firms to face a downward sloping demand curve, our findings suggest that firms may reduce their appropriation in anticipation of the future policy. This is a positive result for regulators since the policy not only entails welfare gains at the period when it is implemented, but potentially in previous periods, as firms exploit the resource at levels close to the social optimum. Specifically, we show that appropriation is more likely to decrease in anticipation of future taxes when: (1) few firms compete for the resource; (2) firms are not price takers in the market where they sell their appropriation; (3) firms do not impose significant cost externalities on each other; and (4) the resource is abundant and/or experiences some regeneration across periods.[2] If some of these

[1] Instead, we focus on CPRs where appropriation levels is socially excessive, such as several fishing grounds and acquifers. According to FAO (2018), the percentage of stocks fished at biologically unsustainable levels increased from 10 percent in 1974 to 33.1 percent in 2015, with the largest increases in the late 1970s and 1980s.

[2] In the context of polluting industries, Marz and Pfeiffer (2015) also identify a production and pollution decrease in the context of a monopolist extracting natural resources, but do not study settings with several firms. Similarly, Nachtigall and Rubbelke (2016) find a similar policy response in the context of resource extraction where firms benefit

conditions do not hold, our findings suggest that the introduction of regulation will induce firms to respond by increasing their first-period appropriation under larger parameter values, partially offseting the welfare-improving effects of regulation during the second period.

In the context of polluting industries exploiting a non-renewable resource, the "green paradox" literature identifies a positive policy response, where firms respond by increasing pollution before the period in which the policy comes into effect.[3] For instance, in an empirical study, Di Maria et al. (2012) finds a 9% increase in the amount of sulphur emitted measured in the period mediating the announcement of Title IV of the Clean Air Act affecting $CO/O_3/SO_2$, in 1990, and its final implementation, in 2000. Similar results apply to Lemoine (2017), who uses future markets data to study the American Clean Energy and Security Act, announced in 2009 and implemented in 2013.[4] Several papers found, instead, industries that react to new policies by reducing their pollution before the implementation of the law; or whose pollution remained unaffected. Hammar and Löfgren (2001), for instance, analyze the Swedish Sulphur Tax, finding a 59% reduction in sulphur dioxide between its announcement, in 1989, and its final implementation, in 1992.[5]

We contribute to the debate of the anticipatory effects of taxation to industries mostly overlooked by the above literature: CPRs where every firm imposes a cost externality on its rivals and standard oligopolies with different degrees of market power. Our results help identify under which contexts we should expect appropriation reductions before regulation comes into effect, which yield unambigous welfare improvements; and under which settings we should, instead, anticipate a more intense exploitation of the resource before the policy is implemented, yielding more ambiguous welfare gains in this case. Our findings suggest that policy makers regulating CPRs where some of the above four conditions hold should expect that policy announcements lead to lower appropriation levels, even before the policy enactment.

Section 2 presents our model. Section 3 then analyzes equilibrium results, as well as its comparative statics. Section 4 discusses our policy implications.

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from learning-by-doing.

[3] As initially suggested by Sinn (2008), the "green paradox" refers to the possibility that climate policies, such as emission fees, which are aimed at reducing carbon emissions, instead lead to an increase in emissions; see Jensen et al. (2015) for a detailed literature review.

[4] For other contributions to this literature considering price-taking firms, see Strand (2007), Hoel (2010), Werf and Di Maria (2011), Smulders et al. (2012), Ploeg (2013), and Di Maria et al. (2012). Other contributions include Grafton et al. (2012) and Van der Ploeg and Withagen (2012).

[5] Other empirical studies reporting significant reductions in pollutants after the policy announcement and before its implementation include Malik and Elrod (2017) in the pulp, paper, and paperboard industries; Agnolucci and Ekins (2004) for $CO_2$ emissions; and the Swedish Environmental Protection Agency Report (2000) for shulphur dioxide. Di Maria et al. (2014) finds no significant change in coal use after the announcement of the Acid Rain Policy, affecting the coal industry and $SO_2$ emitting firms, between its announcement in 1990 and its enactment in 1995.

## 2 Model

Consider an industry where $N \geq 2$ firms compete in quantities, facing a linear inverse demand $p(X) = 1 - bX$, where $b \geq 0$ and $X$ denotes aggregate output. Every firm $i$ faces cost function

$$C(x_i, x_{-i}) = \frac{x_i(x_i + \lambda x_{-i})}{\theta}$$

during the first period, where $\theta$ represents the total stock, $x_i$ denotes firm $i$'s appropriation, and $x_{-i} \equiv \sum_{j \neq i} x_j$ represents the aggregate appropriation by all other $N-1$ firms. Total cost is, therefore, increasing and convex in firm $i$'s appropriation, $x_i$. Firm $i$'s cost is also increasing and convex in its rivals' appropriation $x_{-i}$ if $\lambda > 0$. Therefore, parameter $\lambda \in [0, 1]$ indicates the extent of the cost externality that every firm's appropriation imposes on its rival, e.g., fishing for firm $i$ becomes more costly as firm $j$ increases its appropriation. When $\lambda = 0$, total cost collapses to $\frac{x_i^2}{\theta}$, thus being independent on firm $j$'s appropriation; whereas when $\lambda = 1$, the cost function becomes $\frac{x_i(x_i+x_{-i})}{\theta}$. Finally, total and marginal costs are decreasing in the stock's abundance, $\theta$; and we assume that aggregate appropriations cannot exceed the total stock, $\theta > X$.

In the second period, every firm faces a similar cost function as in the first period

$$C(q_i, q_{-i}) = \frac{q_i(q_i + \lambda q_{-i})}{\theta - (1 - \beta)(x_i + x_{-i})}$$

where $q_i$ denotes firm $i$'s second-period appropriation, $q_{-i}$ represents aggregate appropriation by firm $i$'s rivals, and $\beta \in [0, 1]$ captures the stock's degree of regeneration. When $\beta = 0$, the stock does not regenerate, and first-period appropriation $(x_i + x_{-i})$ reduces the initial stock $\theta$ by exactly $(x_i + x_{-i})$. In contrast, when the stock fully regenerates across periods, $\beta = 1$, first-period appropriation does not decrease available stock at the beginning of the second period. In this case, the second-period cost function becomes $C(q_i, q_j) = \frac{q_i(q_i+\lambda q_{-i})}{\theta}$, thus being symmetric to that in the first period.

Our model thus embodies standard CPR models as a special case when $b = 0$ and $\lambda > 0$. In this setting, firms take price as given, but their appropriation generates a negative externality on their rivals' costs; who experience a higher appropriation cost since the resource became more depleted. Our model also embodies standard Cournot competition as a special case when $b > 0$ and $\lambda = 0$. In this context, every firm's sales affect market prices, but its appropriation does not entail a cost externality on other firms. Finally, we allow for mixed settings where prices are not given, $b > 0$, and externalities are present, $\lambda > 0$.

The time structure of the game is the following:

1. **First period.** Every firm $i \in N$ simultaneously and independently chooses its first-period appropriation $x_i$ not subject to fees.

2. **Second period.**

(a) Fee $t$ comes into effect at the beginning of the second period.

(b) Observing both fee $t$ and the profile of first-period exploitation $(x_1, x_2, ..., x_N)$, every firm $i$ simultaneously and independently chooses its second-period appropriation $q_i$.

Therefore, in the first period every firm $i$ solves

$$\max_{x_i \geq 0} \ \pi_i(X) = (1 - bX)x_i - \frac{x_i(x_i + \lambda x_{-i})}{\theta} \tag{1}$$

where $X \equiv x_i + x_{-i}$ represents first-period aggregate appropriation. Similarly, in the second period, every firm $i$ solves

$$\max_{q_i \geq 0} \ \pi_i(Q) = (1 - bQ)q_i - \frac{q_i(q_i + \lambda q_{-i})}{\theta - (1-\beta)(x_i + x_{-i})} - tq_i \tag{2}$$

where $Q \equiv q_i + q_{-i}$ indicates second-period aggregate appropriation. For simplicity, we consider that demand does not change across periods. Relative to expression (1), the profit in (2) indicates that firm $i$ faces a more depleted resource, and faces a per-unit fee $t \geq 0$. As described below, this is a usage fee that the regulator sets to control the appropriation of the resource.

**Social planner.** Social welfare in the first period, when fees are absent, is given by

$$SW_1(X) \equiv CS_1(X) + PS_1(X)$$

thus accounting for consumer surplus, $CS_1(X) \equiv \frac{1}{2}bX^2$; producer surplus, and $PS_1(X) \equiv \pi_i(X) + \pi_j(X)$. In the second period firms face fee $t$, and welfare becomes

$$SW_2(Q(t)) \equiv CS_2(Q(t)) + PS_2(Q(t)) + T$$

which now includes tax revenue $T$ to guarantee that fees are revenue neutral.

**Policy response (PR).** In the next section, we seek to measure the "policy response" of first-period appropriation ($PR$), as follows

$$PR \equiv x_i(t^*) - x_i(0),$$

When $PR > 0$, this expression indicates that first-period output increases from $x_i(0)$, when fees are absent, to $x_i(t^*)$, evaluated at the second-period fee $t^*$ that the regulator selects in equilibrium. A positive value for $PR$ would indicate that firms, anticipating the future CPR policy during the second period, increase their first-period production, hence depleting the resource more intensively than when the policy is absent. In contrast, a negative $PR$ suggests that firms respond to policy announcements by decreasing their current production in order to reduce their future taxes.

# 3 Equilibrium analysis

We solve the above sequential-move game by backward induction.

## 3.1 Second stage

**Second-period output.** In the second period, every firm $i$ solves

$$\pi_i(t) \equiv \max_{q_i \geq 0} \left[1 - b\left(q_i + Q_{-i}\right)\right] q_i - \frac{q_i(q_i + \lambda Q_{-i})}{\theta - (1-\beta)X} - tq_i \quad (1)$$

Differentiating with respect to output $q_i$ and solving, we obtain profit-maximizing output $q_i(t) = \frac{(1-t)[\theta-(1-\beta)X]}{2+b(1+N)[\theta-(1-\beta)X]+(N-1)\lambda}$, which is positive since $\theta > X$ and $\beta \in [0,1]$ by definition; and yields second-period profits of $\pi_i(t) = \frac{(1-t)^2[\theta-(1-\beta)X][1+\theta-b(1-\beta)X)]}{[2+b(1+N)[\theta-(1-\beta)X]+(N-1)\lambda]^2}$.

**Optimal fee.** The socially optimal output solves

$$\max_{Q} SW_2(Q) = CS(Q) + PS(Q) \quad (2)$$

At first glance, one could think that the regulator had to maximize the welfare from both periods, rather than that from the second period alone. However, the regulator's fee is sequentially rational, i.e., it maximizes social welfare from this point forward, and thus coincides with the above program. Solving for socially optimal output $Q^{SO}$, yields

$$Q^{SO} = \frac{N\left[\theta - (1-\beta)X\right]}{2 + bN\left[\theta - (1-\beta)X\right] + 2(N-1)N\lambda}$$

Therefore, the optimal fee $t^*$ solves $Q^{SO} = Q(t)$, where $Q(t) \equiv \sum_{i=1}^{N} q_i(t)$ denotes aggregate second-period output; as found above. Solving for fee $t$, yields

$$t^* = \frac{b\left[(1-\beta)X - \theta\right] + \lambda(1-N)}{2\lambda(N-1) + 2 + bN\left[\theta - (1-\beta)X\right]}$$

which is positive for all $\lambda > \overline{\lambda} \equiv \frac{b[(1-\beta)X-\theta]}{N-1}$. Intuitively, when the cost externality that firms impose on each other is sufficiently severe, $t^*$ is a tax that discourages appropriation while otherwise $t^*$ becomes a subsidy. The optimal fee is increasing in aggregate first-period output, $X$, and in the number of firms competing for the resource, $N$, since $\beta \in [0,1]$ by definition; but decreasing in the regeneration rate, $\beta$, and in the available stock, $\theta$, for all $\lambda, b \neq 0$.[6] Intuitively, when the resource is more heavily used in the first period and/or more firms compete for it, aggregate appropriation

[6]In particular, the derivative of fee $t^*$ with respect to $X$ is $\frac{\partial t^*}{\partial X} = \frac{b(1-\beta)\left[2+\lambda(N^2+N-2)\right]}{[2\lambda(N-1)+2+bN[\theta-X(1-\beta)]]^2}$, which is positive since $N \geq 1$ by definition. Similarly, $\frac{\partial t^*}{\partial N} = \frac{2\lambda+b[\theta-X(1-\beta)][b[\theta-X(1-\beta)]+3\lambda]}{[2\lambda(N-1)+2+bN[\theta-X(1-\beta)]]^2}$ is also positive since $N \geq 2$ and $\theta > X$ by assumption (i.e., exploitation cannot exceed the available stock). Finally, $\frac{\partial t^*}{\partial \beta} = -\frac{bX\left[2+\lambda(N^2+N-2)\right]}{[2\lambda(N-1)+2+bN[\theta-X(1-\beta)]]^2}$.and $\frac{\partial t^*}{\partial \theta} = -\frac{b\left[2+\lambda(N^2+N-2)\right]}{[2\lambda(N-1)+2+bN[\theta-X(1-\beta)]]^2}$, which are both negative by definition.

becomes socially excessive, inducing a more stringent fee. In contrast, when a larger share of the resource regenerates across periods, first-period appropriation produces a smaller welfare loss in the second period (when policy becomes effective), implying that aggregate appropriation is not different from the social optimum, and thus a lax fee is in order. The optimal fee, however, is decreasing in the severity of external effects, $\lambda$, when $\lambda < \overline{\lambda} \equiv \frac{b[\theta - X(1-\beta)]}{N-1}$, but increasing otherwise.

### 3.2 First period

In the first period, every firm $i$ solves

$$\max_{x_i \geq 0} \; [1 - b(x_i + X_{-i})] \, x_i - \frac{x_i(x_i + \lambda X_{-i})}{\theta} + \delta \pi_i(t^*) \tag{3}$$

where $\delta \in [0, 1]$ denotes the discount factor. The profit function in problem (3), $\pi_i(t^*)$ —the value function of firm $i$'s second-period problem— is evaluated at the optimal fee $t^*$ found above, since the firm can anticipate the fee effective in the subsequent stage of the game, that is,

$$\pi_i(t^*) = \frac{[\theta - (1-\beta)(x_i + X_{-i})] \, [1 + \theta + b(\theta - (1-\beta)(x_i + X_{-i}))]}{[2\lambda(N-1) + 2 + bN \, [\theta - (1-\beta)(x_i + X_{-i})]]^2}.$$

While second-period equilibrium profit without regulation, $\pi_i(0)$, decreases in the number of firms competing for the resource, $N$, that under regulation, $\pi_i(t^*)$, increases in $N$. Intuitively, regulation helps firms reduce their appropriation level, making them internalize the externality they impose on each other, and approaching this appropriation to the amount they would choose under a cartel.

Differentiating problem (3) with respect to first-period appropriation, $x_i$, yields a highly non-linear equation which does not allow for an analytical expression of $x_i^* (t^*)$. Table I numerically evaluates $x^* (t^*)$ at different $(b, \lambda)$-pairs, where $\theta = \delta = 1$, $N = 2$ and $\beta = 2/3$. (We consider other parameter values below.)

| $b$ | $\lambda$ | $\overline{x}_i$ | $x_i^* (t^*)$ | $x_i^* (0)$ | $PR$ |
|---|---|---|---|---|---|
| 0 | 1 | 0.33 | 0.326 | 0.321 | 0.005 |
| 0.5 | 1 | 0.22 | 0.218 | 0.218 | 0 |
| 1 | 0.5 | 0.18 | 0.178 | 0.180 | $-0.002$ |
| 1 | 0 | 0.20 | 0.195 | 0.198 | $-0.003$ |

Table I. First-period appropriation and firms' policy response.

Specifically, the table reports the upper bound on appropriation, $\overline{x}_i$, which solves (3) but considering that firms place no weight on future profits, $\delta = 0$, that is, $\overline{x}_i = \frac{\theta}{\theta(N+1)b + (N-1)\lambda + 2}$. Intuitively, this bound indicates that equilibrium appropriation should not exceed the optimal appropriation level when firms ignore their future payoffs.[7] In addition, it provides first-period appropriation with and without regulation, $x_i^*(t^*)$ and $x_i^*(0)$, respectively. The value of $x_i^*(0)$ is found by evaluating second-period output $q_i(t)$ at $t = 0$, $q_i(0)$, as well as second-period profit $\pi_i(0)$, which can then be inserted into (3) to obtain $x_i^*(0)$. Finally, the table also reports the policy response $PR = x_i^*(t^*) - x_i^*(0)$, measuring the increase in appropriation that results from the introduction of the policy (if $PR > 0$) or the policy-induced reduction in appropriation (if $PR < 0$).

For illustration purposes, Figure 1 considers those $(b, \lambda)$-pairs in Table I, as well as other $(b, \lambda)$ combinations, and reports the $PR$ next to each point.[8] First, when firms compete in a standard CPR (taking prices as given, $b = 0$, but generating external effects on each other, $\lambda > 0$), our results show a positive $PR$. This is illustrated in the horizontal axis, confirming the finding in the green paradox literature, namely, that firms increase their first-period appropriation anticipating the loss in future profits they will experience in the second period under regulation.[9] Second, when firms compete a la Cournot ($b > 0$ and $\lambda = 0$), we show a negative $PR$; as depicted in the points along the vertical axis. Third, the figure reports $(b, \lambda)$-pairs with positive $PR$ when the market structure is relatively similar to a standard CPR —low values of $b$ and high values of $\lambda$— but a negative $PR$ when firms do not take prices as given.

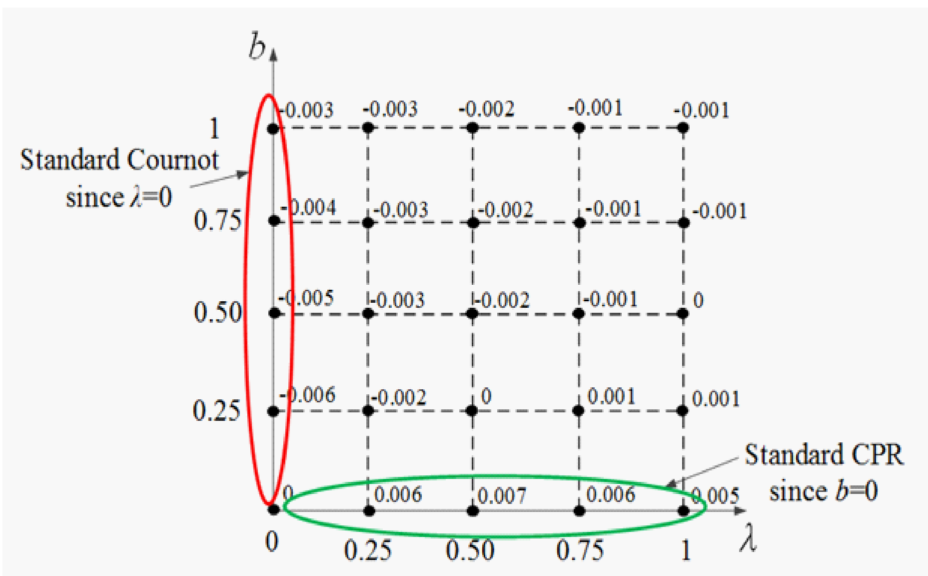


Figure 1. Policy response under different settings.

[7]The numerical evaluation of first-period appropriation $x_i^*(t^*)$ provides several roots. Hence, the upper bound $\overline{x}_i$ helps us identify the feasible appropriation level.

[8]For instance, when $b = 1$ and $\lambda = 0.5$, as described in the fourth row of Table I, $PR = -0.002$, as depicted next to point $(b, \lambda) = (1, 0.5)$ in the far right-hand side of Figure 1.

[9]When $b = 0$, the first-order condition from problem (3) yields an analytical expression for the optimal first-period output with regulation, $x_i^*(t^*)$, and without regulation, $x_i^*(0)$. This is the only case in which an analytical solution can be found. In particular, $x_i^*(t^*) = \frac{\theta\left[4(1+(N-1)\lambda)^2-(1-\beta)\delta\right]}{4[1+(N-1)\lambda]^2(2+(N-1)\lambda)}$ and $x_i^*(0) = \frac{\theta\left[(2+(N-1)\lambda)^2-(1-\beta)\delta\right]}{[2+(N-1)\lambda]^3}$, thus yielding a policy response $PR = \frac{(N-1)(1-\beta)\delta\theta\lambda(4+3(N-1)\lambda)}{4[1+(N-1)\lambda]^2[2+(N-1)\lambda]^3}$, which is positive since $N \geq 2$ and $\beta \in [0, 1]$ by definition.

Intuitively, for a given value of $\lambda$, a first-period output reduction entails no change in market prices when firms are price takers (as in standard CPRs where $b = 0$). However, when $b > 0$, this output reduction produces an increase in market prices, making it more attractive for the firm than when $b = 0$. Therefore, regulation not only decreases second-period output, but can also reduce first-period output (before coming into effect) if firms face a downward sloping demand curve. Figure 1 also suggests that, for a given $b > 0$ (such as $b = 0.50$), a more severe cost externality (higher $\lambda$) produces a nil or positive $PR$. In words, this indicates that regulation yields either a negligible decrease (or even an increase) in first-period appropriation when firms generate a severe externality on each others' costs. In this setting, firms anticipate a more stringent fee in the second period, responding with a larger appropriation with than without regulation to partially compensate for their future profit loss.

### 3.3 Comparative statics

Figure 2a illustrates $PR$s with a scarcer stock, $\theta = 1/2$, keeping all other parameter values unchanged. Relative to Figure 1, Figure 2a shows that $PR$ becomes negative under more restrictive $(b, \lambda)$-pairs. Intuitively, a scarcer resource leads to a more stringent fee (since $t^*$ and $\theta$ move in opposite directions), inducing firms to increase their first-period appropriation under larger parameter conditions. Figure 2b illustrates similar findings when the regeneration rate is smaller, $\beta = 1/3$, since in this case the fee also becomes more stringent.

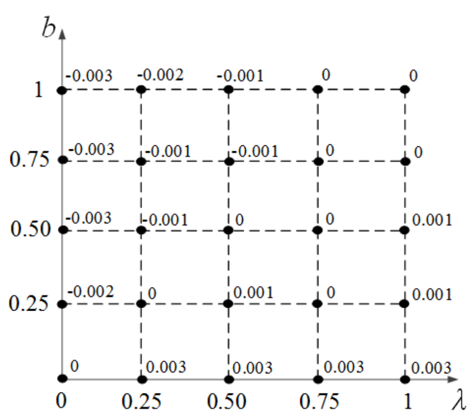


Fig. 2a. $PR$ with $\theta = 1/2$.

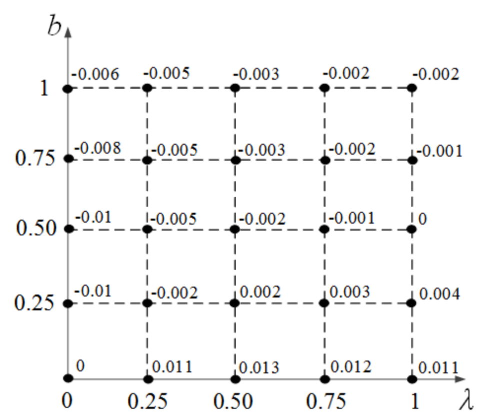


Fig. 2b. $PR$ with $\beta = 1/3$.

Figure 3 reports $PR$s using the same parameters as Figure 1, but allowing for $N = 4$ firms. Figure 3 shows that $PR$ decreases in absolute value, becoming closer to zero for all $(b, \lambda)$-pairs; which occurs both when the $PR$ was positive and when it was negative in Figure 1. In fact, when the number of firms competing for the resource increases to $N = 10$ firms, $PR = 0$ for all $(b, \lambda)$-pairs. Intuitively, firms anticipate that, as shown above, their second-period equilibrium profit $\pi_i(t^*)$ increases in $N$, reducing their incentives to alter their first-period appropriation, so

$x_i^*(t^*) = x_i^*(0)$.

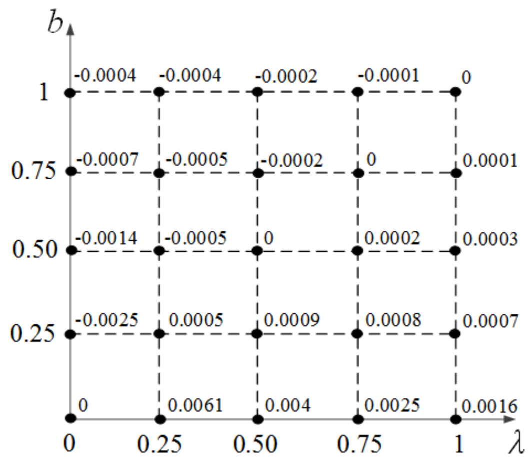


Fig 3. $PR$ with $N = 4$ firms.

### 3.4 Cartel behavior

For completeness, Appendix 2 studies appropriation decisions when firms operate as a cartel, seeking to maximize their joint profits during the first and second periods. Table II summarizes first-period appropriation with and without regulation, and the resulting $PR^C$, where the $C$ superscript denotes cartel. For comparison purposes, we evaluate these expressions at the same parameter values as Table I,[10] showing that when firms operate as a cartel, they internalize the cost externality (when $\lambda > 0$), the price effects (when $b > 0$) or both, and thus exploit the resource less intensively; a result that holds under all parameter combinations, with and without regulation. The cartel, however, produces a smaller reduction in first-period appropriation when firms face regulation, $x_i^C\left(t^C\right)$, than when they do not, $x_i^C\left(0\right)$, ultimately yielding a larger $PR^C$. Intuitively, regulation serves as coordination tool for firms when they do not form a cartel, helping them approach to cartel appropriation levels; which implies that regulating a cartel does not alter exploitation decision so significantly. In conclusion, the pollution reduction effects that can arise when firms do not act as a cartel, $PR < 0$, are less likely to emerge when firm operate as such.

| $b$ | $\lambda$ | $\overline{x}_i^C$ | $x_i^C\left(t^C\right)$ | $x_i^C\left(0\right)$ | $PR^C$ |
|---|---|---|---|---|---|
| 0 | 1 | 0.166 | 0.1632 | 0.1527 | 0.0104 |
| 0.5 | 1 | 0.125 | 0.1226 | 0.1201 | 0.0025 |
| 1 | 0.5 | 0.111 | 0.1090 | 0.1086 | 0.0004 |
| 1 | 0 | 0.125 | 0.1222 | 0.1224 | $-0.0001$ |

[10] Other parameter values produce similar results, and can be provided by the authors upon request.

Table II. First-period appropriation and the policy response under cartel.

## 4 Introducing pollution damages

In this section, we allow for appropriation to generate pollution, such as water discharges from vessels or other pollutants firms exploiting a CPR emit in their activities. Social welfare is symmetric to the expressions considered in previous sections, thus accounting for consumer and producer surplus, but now includes an additional term capturing the environmental damage from pollution. In the first period, when fees are absent, social welfare is

$$SW_1(X) \equiv CS_1(X) + PS_1(X) - dX^2$$

where the last term, $dX^2$, represents the convex environmental damage from aggregate first-period appropriation, $X$, and $d > 0$. In the second period, firms face fee $t$, and welfare becomes

$$SW_2(Q(t)) \equiv CS_2(Q(t)) + PS_2(Q(t)) + T - d(Q + \gamma X)Q$$

where parameter $\gamma \in [0, 1]$ denotes the damage persistence of first-period appropriation, $X$. When $\gamma = 0$, second-period environmental damage collapses to $dQ^2$, but when $\gamma = 1$ every unit of first-period appropriation, $X$, also generates damages in the second period.

For compactness, Appendix 3 solves our sequential-move game again in this context. Table III summarizes first-period appropriation and the firms' policy response in this setting, comparing it against that when pollution was not considered in Table I. For comparison purposes, we evaluate all variables at the same parameter values as in Table I.[11]

| $b$ | $\lambda$ | $\overline{x}_i$ | $x_i^*\,(t^*)$ | $x_i^*\,(0)$ | $PR$ with pollution | $PR$ without pollution |
|---|---|---|---|---|---|---|
| 0 | 1 | 0.33 | 0.327 | 0.321 | 0.011 | 0.005 |
| 0.5 | 1 | 0.22 | 0.217 | 0.218 | 0.003 | 0 |
| 1 | 0.5 | 0.18 | 0.175 | 0.180 | 0.001 | $-0.002$ |
| 1 | 0 | 0.20 | 0.191 | 0.198 | 0.001 | $-0.003$ |

Table III. Firms' policy response with/without pollution.

Table III indicates that policy responses are more likely to become positive when firms are subject to a tax seeking to curb pollution (i.e., emission fee) than when appropriation does not yield environmental damages (i.e., usage fees). This result is confirmed in figure 4, which is symmetric to figure 1 in a context with environmental damage. Intuitively, the emission fee is more stringent than the usage fee; as the former seeks to alleviate two market failures, a socially excessive pollution and

[11] The only new parameters relative to Table I are $d$ and $\gamma$, which are evaluated at $d = 1/2$ and $\gamma = 0$ in Table III. Other parameter values yield qualitatively similar results.

appropriation, while the latter only seeks to curb a socially excessive appropriation. In anticipation of a more stringent fee in the second period, firms are more likely to increase their first-period appropriation. Therefore, a positive $PR$, and their associated welfare losses during the first period, are more substantial when regulators use emission fees to reduce pollution in CPRs than when they use usage fees to only decrease a socially excessive appropriation of the resource.

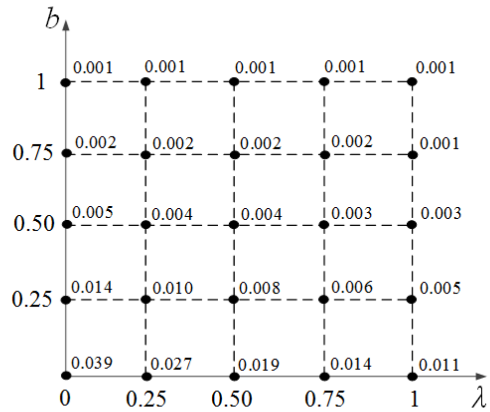


Fig. 4. $PR$ with environmental damage.

## 5 Discussion

*Anticipatory effects of taxation.* Our above results indicate that firms respond to future regulation by altering their first-period appropriation decisions, that is, fees are effective even before they are implemented. In addition, we showed that the $PR$, understood as how much firms increase their first-period appropriation in anticipation of future fees, is not necessarily positive, as suggested by the literature, but can also be negative, or zero, depending on the market structure where firms interact. Our findings then indicate that regulators should carefully consider industry characteristics when designing policy. In particular, if regulators value negative $PR$s —where firms reduce their appropriation levels even before the policy comes into effect— they should seek CPRs where: (1) firms are not price takers in the market where they sell their appropriation (relatively high $b$); (2) firms do not impose significant cost externalities on each other (relatively low $\lambda$); (3) the stock is abundant (relatively high $\theta$); (4) the resource experiences some regeneration across periods (high $\beta$); and (5) few firms compete for the resource (low $N$). If some of these conditions do not hold, our findings suggest that the introduction of fees will induce firms to respond by increasing their first-period appropriation under larger parameter values, ultimately inducing a positive $PR$. This partially offsets the welfare-improving effects of regulation during the second period. In contrast, when the above conditions hold, we showed that a negative $PR$ is more likely. In words, this entails that the introduction of policy can yield not only welfare benefits during the second period, when the regulation comes into effect, but also during the first period since firms respond to the future policy by reducing their first-period appropriation.

*Comparing profits with/without taxes.* Emission fees produce a strict decrease in second-period profits, and a weak reduction in first-period profits. To understand this point, note that, in the second period, firm profits are lower with than without taxes, since every firm produces a suboptimal amount.[12] In the first period, the firm increases (decreases) its production when $PR > 0$ ($PR < 0$, respectively), but deviates away from its first-period exploitation level without regulation $x_i^*(0)$, thus obtaining lower first-period profits than when firms are not subject to fees. However, when the number of firms competing for the resource is sufficiently large, $PR$ is close to zero, entailing that firms do not change their first-period appropriation decisions because of their anticipation of future taxes. Therefore, when several firms compete, the introduction of fees produces an unambiguous decrease in second-period profits, but no change whatsoever in first-period profits.

*First-period efficiency gains?* During the second period (when the fee is implemented), the tax induces firms to exactly produce the social optimum. In the first period, however, fees are not enacted yet but, in anticipation of the tax, firms reduce (increase) their production thus decreasing (increasing) pollution; moving first-period output closer (farther away, respectively) to the social optimum. However, when several firms compete for the resource, our results show that the $PR$ approaches zero, indicating that the efficiency gain (loss) that the second-period regulation brings into the first-period vanish.

# 6 Appendix 1

The following tables report the $PR$ for each $(b, \lambda)$-pair in Figures 1, 2a, 2b, and 3, respectively.

[12] That is, even if the emission fee is revenue neutral and the regulator returns all tax collection to the firms as a lump-sum subsidy, under regulation every firm chooses an appropriation level different from that under no regulation (which maximizes its profit function).

| $b$ | $\lambda$ | $\bar{x}_i$ | $x_i^*(t^*)$ | $x_i^*(0)$ | $PR$ |
|---|---|---|---|---|---|
| 0 | 0 | 0.500 | 0.458 | 0.458 | 0 |
| 0 | 0.25 | 0.444 | 0.421 | 0.415 | 0.006 |
| 0 | 0.5 | 0.400 | 0.385 | 0.378 | 0.007 |
| 0 | 0.75 | 0.364 | 0.354 | 0.348 | 0.006 |
| 0 | 1 | 0.333 | 0.326 | 0.321 | 0.005 |
| 0.25 | 0 | 0.360 | 0.342 | 0.348 | -0.006 |
| 0.25 | 0.25 | 0.333 | 0.319 | 0.321 | -0.002 |
| 0.25 | 0.5 | 0.308 | 0.298 | 0.298 | 0.000 |
| 0.25 | 0.75 | 0.286 | 0.278 | 0.277 | 0.001 |
| 0.25 | 1 | 0.270 | 0.261 | 0.260 | 0.001 |
| 0.5 | 0 | 0.286 | 0.274 | 0.279 | -0.005 |
| 0.5 | 0.25 | 0.267 | 0.258 | 0.261 | -0.003 |
| 0.5 | 0.5 | 0.250 | 0.243 | 0.245 | -0.002 |
| 0.5 | 0.75 | 0.235 | 0.230 | 0.231 | -0.001 |
| 0.5 | 1 | 0.22 | 0.218 | 0.218 | 0.000 |
| 0.75 | 0 | 0.240 | 0.228 | 0.232 | -0.004 |
| 0.75 | 0.25 | 0.222 | 0.216 | 0.219 | -0.003 |
| 0.75 | 0.5 | 0.211 | 0.206 | 0.208 | -0.002 |
| 0.75 | 0.75 | 0.200 | 0.196 | 0.197 | -0.001 |
| 0.75 | 1 | 0.190 | 0.187 | 0.188 | -0.001 |
| 1 | 0 | 0.20 | 0.195 | 0.198 | -0.003 |
| 1 | 0.25 | 0.190 | 0.186 | 0.189 | -0.003 |
| 1 | 0.5 | 0.182 | 0.178 | 0.180 | -0.002 |
| 1 | 0.75 | 0.174 | 0.171 | 0.172 | -0.001 |
| 1 | 1 | 0.170 | 0.164 | 0.165 | -0.001 |

| $b$ | $\lambda$ | $\bar{x}_i$ | $x_i^*(t^*)$ | $x_i^*(0)$ | $PR$ |
|---|---|---|---|---|---|
| 0 | 0 | 0.250 | 0.229 | 0.229 | 0 |
| 0 | 0.25 | 0.222 | 0.210 | 0.207 | 0.003 |
| 0 | 0.5 | 0.200 | 0.193 | 0.190 | 0.003 |
| 0 | 0.75 | 0.182 | 0.177 | 0.174 | 0.003 |
| 0 | 1 | 0.167 | 0.163 | 0.160 | 0.003 |
| 0.25 | 0 | 0.211 | 0.196 | 0.198 | -0.002 |
| 0.25 | 0.25 | 0.190 | 0.181 | 0.181 | 0 |
| 0.25 | 0.5 | 0.174 | 0.168 | 0.167 | 0.001 |
| 0.25 | 0.75 | 0.160 | 0.156 | 0.155 | 0.001 |
| 0.25 | 1 | 0.148 | 0.145 | 0.144 | 0.001 |
| 0.5 | 0 | 0.182 | 0.171 | 0.174 | -0.003 |
| 0.5 | 0.25 | 0.167 | 0.160 | 0.161 | -0.001 |
| 0.5 | 0.5 | 0.154 | 0.149 | 0.149 | 0 |
| 0.5 | 0.75 | 0.143 | 0.139 | 0.139 | 0 |
| 0.5 | 1 | 0.133 | 0.131 | 0.130 | 0.001 |
| 0.75 | 0 | 0.160 | 0.152 | 0.155 | -0.003 |
| 0.75 | 0.25 | 0.148 | 0.143 | 0.144 | -0.001 |
| 0.75 | 0.5 | 0.138 | 0.134 | 0.135 | -0.001 |
| 0.75 | 0.75 | 0.129 | 0.196 | 0.196 | 0.000 |
| 0.75 | 1 | 0.121 | 0.119 | 0.119 | 0.000 |
| 1 | 0 | 0.143 | 0.137 | 0.140 | -0.003 |
| 1 | 0.25 | 0.133 | 0.129 | 0.131 | -0.002 |
| 1 | 0.5 | 0.125 | 0.122 | 0.123 | -0.001 |
| 1 | 0.75 | 0.118 | 0.115 | 0.115 | 0 |
| 1 | 1 | 0.111 | 0.109 | 0.109 | 0 |

Table A1. $PR$ for $\theta = \delta = 1$, $\beta = 2/3$, and $N = 2$; and Table A2a. $PR$ for $\theta = 1/2$, $\delta = 1$, $\beta = 2/3$, and $N = 2$.

| $b$ | $\lambda$ | $\bar{x}_i$ | $x_i^*(t^*)$ | $x_i^*(0)$ | $PR$ |
|---|---|---|---|---|---|
| 0 | 0 | 0.500 | 0.417 | 0.417 | 0 |
| 0 | 0.25 | 0.444 | 0.210 | 0.199 | 0.011 |
| 0 | 0.5 | 0.400 | 0.397 | 0.384 | 0.013 |
| 0 | 0.75 | 0.364 | 0.344 | 0.332 | 0.012 |
| 0 | 1 | 0.333 | 0.319 | 0.308 | 0.011 |
| 0.25 | 0 | 0.364 | 0.317 | 0.327 | -0.010 |
| 0.25 | 0.25 | 0.333 | 0.303 | 0.305 | -0.002 |
| 0.25 | 0.5 | 0.308 | 0.287 | 0.285 | 0.002 |
| 0.25 | 0.75 | 0.286 | 0.271 | 0.268 | 0.003 |
| 0.25 | 1 | 0.267 | 0.256 | 0.252 | 0.004 |
| 0.5 | 0 | 0.286 | 0.259 | 0.269 | -0.010 |
| 0.5 | 0.25 | 0.267 | 0.247 | 0.252 | -0.005 |
| 0.5 | 0.5 | 0.250 | 0.235 | 0.237 | -0.002 |
| 0.5 | 0.75 | 0.235 | 0.224 | 0.225 | -0.001 |
| 0.5 | 1 | 0.222 | 0.214 | 0.214 | 0.000 |
| 0.75 | 0 | 0.235 | 0.219 | 0.227 | -0.008 |
| 0.75 | 0.25 | 0.222 | 0.209 | 0.214 | -0.005 |
| 0.75 | 0.5 | 0.211 | 0.200 | 0.203 | -0.003 |
| 0.75 | 0.75 | 0.200 | 0.191 | 0.193 | -0.002 |
| 0.75 | 1 | 0.190 | 0.184 | 0.185 | -0.001 |
| 1 | 0 | 0.200 | 0.189 | 0.195 | -0.006 |
| 1 | 0.25 | 0.190 | 0.181 | 0.186 | -0.005 |
| 1 | 0.5 | 0.182 | 0.174 | 0.177 | -0.003 |
| 1 | 0.75 | 0.174 | 0.167 | 0.169 | -0.002 |
| 1 | 1 | 0.167 | 0.161 | 0.163 | -0.002 |

| $b$ | $\lambda$ | $\bar{x}_i$ | $x_i^*(t^*)$ | $x_i^*(0)$ | $PR$ |
|---|---|---|---|---|---|
| 0 | 0 | 0.500 | 0.4580 | 0.4580 | 0 |
| 0 | 0.25 | 0.364 | 0.3540 | 0.3479 | 0.0061 |
| 0 | 0.5 | 0.286 | 0.2820 | 0.2780 | 0.0040 |
| 0 | 0.75 | 0.235 | 0.2330 | 0.2305 | 0.0025 |
| 0 | 1 | 0.200 | 0.1990 | 0.1974 | 0.0016 |
| 0.25 | 0 | 0.308 | 0.2960 | 0.2985 | -0.0025 |
| 0.25 | 0.25 | 0.250 | 0.2450 | 0.2445 | 0.0005 |
| 0.25 | 0.5 | 0.211 | 0.2080 | 0.2071 | 0.0009 |
| 0.25 | 0.75 | 0.182 | 0.1810 | 0.1802 | 0.0008 |
| 0.25 | 1 | 0.160 | 0.1590 | 0.1583 | 0.0007 |
| 0.5 | 0 | 0.222 | 0.2190 | 0.2204 | -0.0014 |
| 0.5 | 0.25 | 0.190 | 0.1880 | 0.1885 | -0.0005 |
| 0.5 | 0.5 | 0.167 | 0.1650 | 0.1650 | 0.0000 |
| 0.5 | 0.75 | 0.148 | 0.1470 | 0.1468 | 0.0002 |
| 0.5 | 1 | 0.133 | 0.1330 | 0.1327 | 0.0003 |
| 0.75 | 0 | 0.174 | 0.1720 | 0.1727 | -0.0007 |
| 0.75 | 0.25 | 0.154 | 0.1530 | 0.1535 | -0.0005 |
| 0.75 | 0.5 | 0.138 | 0.1370 | 0.1372 | -0.0002 |
| 0.75 | 0.75 | 0.125 | 0.1240 | 0.1240 | 0.0000 |
| 0.75 | 1 | 0.114 | 0.1140 | 0.1139 | 0.0001 |
| 1 | 0 | 0.143 | 0.1420 | 0.1424 | -0.0004 |
| 1 | 0.25 | 0.129 | 0.1280 | 0.1284 | -0.0004 |
| 1 | 0.5 | 0.118 | 0.1170 | 0.1172 | -0.0002 |
| 1 | 0.75 | 0.108 | 0.1080 | 0.1081 | -0.0001 |
| 1 | 1 | 0.100 | 0.1000 | 0.1000 | 0.0000 |

Table A2b. $PR$ for $\theta = \delta = 1$, $\beta = 1/3$, and $N = 2$; and Table A3. $PR$ for $\theta = \delta = 1$, $\beta = 2/3$, and $N = 4$.

# 7 Appendix 2 - Cartel appropriation

In this appendix, we explore how our results are affected when firms coordinate their appropriation decisions in a cartel seeking to maximize their joint profits during the first and second periods. In the second period, the cartel solves

$$\pi^C(t) \equiv \max_{q_1,\ldots,q_N \geq 0} \sum_{i=1}^{N} \left[ \left[1 - b\left(q_i + Q_{-i}\right)\right] q_i - \frac{q_i(q_i + \lambda Q_{-i})}{\theta - (1-\beta)X} - tq_i \right] \tag{A1}$$

where superscript $C$ denotes cartel. Differentiating with respect to output $q_i$ and solving, we obtain profit-maximizing output for every firm $i$ of $q_i^C(t) = \frac{(2-t)[\theta-(1-\beta)X]}{2(N-1)[b(\theta-(1-\beta)X)+\lambda]}$; which yields second-period profits of $\pi_i(t) = \frac{(1-t)^2[\theta-(1-\beta)X]}{4[1+bN[\theta-(1-\beta)X]+(N-1)\lambda]}$. Socially optimal output in this setting coincides with that found in problem (2) in the main body of the paper, $Q^{SO}$. The optimal fee under cartel $t^C$, however, now solves $Q^{SO} = Q^C(t)$, where $Q^C(t) \equiv \sum_{i=1}^{N} q_i^C(t)$ denotes aggregate second-period cartel output, which yields

$$t^C = \frac{N-1}{N} - \frac{b\left[\theta - (1-\beta)X\right]}{2 + bN\left[\theta - (1-\beta)X\right] + 2\lambda(N-1)}$$

entailing second-period profits (evaluated at fee $t^C$) of

$$\pi^C(t^C) = N\frac{\left[\theta - (1-\beta)(x_i + X_{-i})\right]\left[1 + bN(\theta - (1-\beta)(x_i + X_{-i}) + \lambda(N-1))\right]}{N^2\left[2 + bN\left[\theta - (1-\beta)(x_i + X_{-i})\right] + 2\lambda(N-1)\right]^2}.$$

In the first period, the cartel solves

$$\max_{x_1,\ldots,x_N \geq 0} \sum_{i=1}^{N} \left[ \left[1 - b(x_i + X_{-i})\right] x_i - \frac{x_i(x_i + \lambda X_{-i})}{\theta} + \delta\pi^C(t^C) \right] \tag{A2}$$

where profit $\pi^C(t^C)$ was defined above. As in the main body of the paper, differentiating for every firm's first-period appropriation $x_i$ produces a highly non-linear equation, which does not allow for analytical solutions of the optimal $x_i^C$. For comparison purposes, Table II in the main body of the paper evaluates $x_i^C(t^C)$, $x_i^C(0)$, and their difference $(PR)$ at the same parameter values as Table I. Finally, the upper bound for first-period appropriation in this setting, $\overline{x}_i^C$, is equivalent to solving (A2) above at $\delta = 0$, which yields $\overline{x}_i^C = \frac{\theta}{2[N(1+\lambda+b\theta)-\lambda]}$.

# 8 Appendix 3 - Allowing for environmental damages

In this appendix, we solve the sequential-move game again, but allowing for environmental damages; as presented in Section 3.5.

**Second period.** In the second period, every firm solves problem (1), thus yielding the same profit-maximizing output $q_i(t)$ and second-period profits $\pi_i(t)$ as in Section 3.1. The regulator then solves a problem analogous to (2), but including the environmental damage from appropriation, as follows

$$\max_{Q} SW_2(Q) = CS(Q) + PS(Q) + T - (dQ + \gamma dX)Q \tag{2'}$$

Solving for socially optimal output $Q^{SO}$, yields

$$Q^{SO} = -\frac{N(dX\gamma - 1)(X(\beta - 1) + \theta)}{2 - N(b\alpha - 2(b + d))(X(\beta - 1) + \theta) - 2\lambda(1 + N)}$$

Therefore, the optimal emission fee $t^*$ solves $Q^{SO} = Q(t)$, where $Q(t) \equiv \sum_{i=1}^{N} q_i(t)$ denotes aggregate second-period output; as found above. Solving for tax $t$, yields

$$t^* = \frac{b(d(N+1)X\gamma - 1)\left[X(\beta - 1) + \theta\right] + 2d(X\gamma + N(X(\beta - 1) + \theta)) + (N-1)(1 + dX\gamma)\lambda}{2 + (b + 2d)N(X(\beta - 1) + \theta) - 2\lambda(1 - N)}$$

Differentiating the optimal emission fee $t^*$ with respect to $\gamma$, we find

$$\frac{\partial t^*}{\partial \gamma} = \frac{dX\left[2 + b(N+1)X(\beta - 1) + \theta\right] + (N-1)\lambda)}{2 + (b + 2d)N(X(\beta - 1) + \theta) + 2\lambda(N - 1)} > 0$$

which is positive since, in the numerator, term $(X(\beta - 1) + \theta) + (N - 1)\lambda$ is positive because $\theta > X(\beta - 1)$ and $(N - 1)\lambda \geq 0$; yielding a positive numerator. The denominator is also positive because, again, $\theta > X(\beta - 1)$ and $2\lambda(N - 1) \geq 0$. Therefore, a larger damage persistence of first-period appropriation into the second period induces the regulator to set a more stringent emission fee $t^*$.

Differentiating the optimal emission fee $t^*$ with respect to $d$, we obtain

$$\frac{\partial t^*}{\partial d} = \frac{\left[2 + b(N+1)\left[X(\beta - 1) + \theta\right] + (N-1)\lambda\right]\left[N(2 + bX\gamma)\left[X(\beta - 1) + \theta\right] + 2X\gamma(1 - \lambda) + 2NX\gamma\lambda\right]}{\left[2 + (b + 2d)N\left[X(\beta - 1) + \theta\right] + 2\lambda(N - 1)\right]^2} > 0$$

which is also positive since, in the numerator, $\theta > X(\beta - 1)$, $(N - 1)\lambda \geq 0$, and $2X\gamma(1 - \lambda) \geq 0$ since $\lambda \leq 1$; implying that the numerator is positive. The denominator is squared so it is alos positive. As a consequence, a larger environmental damage from first- or second-period appropriation, $d$, leads the regulator to set a more stringent emission fee.

**First period.** In the first period, every firm $i$ solves

$$\max_{x_i \geq 0} \quad \left[1 - b(x_i + X_{-i})\right] x_i - \frac{x_i(x_i + \lambda X_{-i})}{\theta} + \delta \pi_i(t^*) \qquad (3')$$

which is analogous to problem (3) in Section 3.2, except for the fact that the firm's second-period equilibrium profit under regulation is now evaluated at a different emission fee $t^*$, that is,

$$\pi(t^*) = \frac{(dX\gamma - 1)^2\left[X(\beta - 1) + \theta\right]\left[1 + b\left[X(\beta - 1) + \theta\right]\right]}{\left[2 + (b + 2d)N(X(\beta - 1) + \theta) - 2\lambda(1 - N)\right]^2}$$

Differentiating problem (3) with respect to $x_i$, we obtain a rather intractable first-order condition which does not allow us to explicitly solve for $x_i$ to obtain the equilibrium first-period appropriation. For comparison purposes, we evaluate the resulting first-order conditions at the same parameter values as Table I, yielding Table III, as reported in Section 3.5.

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