Anticipatory Effects of Taxation in the Commons: *When does it work, and when does it fail?**

Ana Espinola-Arredondo[†], Félix Muñoz-García[‡], and Isaac Duah[§]
School of Economic Sciences
Washington State University
Pullman, WA 99164

April 5, 2019

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 increases in resource exploitation before the policy comes into effect, thus offsetting their subsequent welfare-improving effects.

Keywords: Common-pool resources, Environmental policy, Anticipatory effects.
JEL classification: H23; L13; Q5.

*We are grateful to the editor, Stefan Baumgaertner, and three anonymous referees for their valuable comments and their constructive suggestions.

†Address: 111C Hulbert Hall, Washington State University, Pullman, WA 99164. E-mail: anaespinola@wsu.edu.
‡Address: 103H Hulbert Hall, Washington State University, Pullman, WA 99164. E-mail: fmunoz@wsu.edu.
§Address: 205E Hulbert Hall, Washington State University, Pullman, WA 99164. E-mail: isaac.duah@wsu.edu.

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 offsetting 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, planned to become into effect in 2013, but that finally was not implemented as the bill did not come up for a vote in the Senate.[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] Finally, Costello and Kaffine (2008) examine how an insecure property right framework affects the exploitation of a CPR, where renewal may not be granted. They find that uncertainty on renewed concession can induce to efficient exploitation. However, they do not analyze the anticipatory effect of the policy.[6]

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 unambiguous 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 com-

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), Di Maria et al. (2014), 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.

[6] Riekhof and Bröcker (2017), using a general equilibrium model, examine the effect of the announcement of a carbon emissions tax on generation of emissions. However, they do not explicitly examine the strategic effects of this announcement on firms' appropriation level in a CPR and do not identify which specific industry characteristics generate more significant policy responses.

parative statics. Section 4 discusses our policy implications.

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 first-period output. (Our model applies to firms producing output or appropriating a resource, so we use both terms interchangeably.) 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 θ represents the total stock, x_i denotes firm i's appropriation, and $x_{-i} \equiv \sum_{j \neq i} x_j$ represents the aggregate output 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 linearly increasing in its rivals' appropriation x_{-i} if $\lambda > 0$. Therefore, parameter $\lambda \geq 0$ 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, θ, 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 ability to stock's ability to "recover" across periods or, alternatively, its "replacement" rate, that is, to which extent the initial stock θ grows to compensate first-period appropriation, X. When $\beta = 1$, the initial stock θ has a natural regeneration rate that fully compensates for first-period appropriation, X, implying that the initial stock θ is completely available again at the beginning of the second period. In contrast, when $\beta = 0$, the initial stock θ does not grow at all, entailing that firms face an available stock of $\theta - X$ 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.[7]

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 $\lambda = 0$.

[7] Appendix 5 considers an alternative regeneration function, assuming the second-period stock is $\theta(1 + g) - X$, where $g \geq 0$ denotes the initial stock's growth rate. We show that our result are qualitatively unaffected. In addition, appendix 6 examines the case of asymmetric costs, i.e., firm i being less efficient than firm j, also suggesting that our main findings hold.

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.**
   (a) The regulator announces a fee t that will come into effect at the beginning of the second period.
   (b) 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.[8]
   (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, firm i's first-period profit is

$$\pi_i(x_i, x_{-i}) = (1 - bX)x_i - \frac{x_i(x_i + \lambda x_{-i})}{\theta} \tag{1}$$

where $X \equiv x_i + x_{-i}$ represents first-period aggregate appropriation. Let $x_i(t)$ denote the solution to problem (1). Similarly, second-period profit is

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

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

$$SW_1(x_i, x_{-i}) \equiv CS_1(X) + PS_1(x_i, x_{-i})$$

[8] For this fee to be credible, it must be a subgame perfect equilibrium, meaning that it must be optimal for the regulator at the beginning of the second period, rather than revise it at this point of the game. Since in the second period firms already made their first-period appropriation decisions, the regulator can only consider second-period welfare. If, instead, the regulator considered the sum of first- and second-period welfare, the fee that he announces in the first period would not be credible since he could change it at the beginning of the second period.

thus accounting for consumer surplus, $CS_1(X) \equiv \frac{1}{2}bX^2$, producer surplus, and $PS_1(x_i, x_{-i}) \equiv \sum_{i=1}^{N} \pi_i(x_i, x_{-i})$. In the second period firms face fee t, and welfare becomes

$$SW_2(q_i, q_{-i}) \equiv CS_2(Q) + PS_2(q_i, q_{-i}).$$

Policy response (PR). Consider the firm's optimal first-period appropriation that solves problem (1), $x_i(t)$, and evaluate at $t = 0$ to obtain the firm's appropriation when fees are absent, $x_i(0)$, and then at the second-period fee t^* that the regulator selects in equilibrium, t^*, to find the firm's appropriation when fees are present. We can then define the firm's "policy response" (PR), as follows

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

When $PR > 0$, this expression indicates that first-period appropriation increases from $x_i(0)$, when fees are absent, to $x_i(t^*)$, evaluated at the second-period fee t^*. 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 appropriation. In the second period, every firm i solves

$$\pi_i(t) \equiv \max_{q_i \geq 0} \; [1 - b\,(q_i + q_{-i})]\, q_i - \frac{q_i(q_i + \lambda q_{-i})}{\theta - (1-\beta)X} - tq_i \tag{3}$$

Differentiating with respect to output q_i and solving, we obtain the best response function

$$q_i(Q_{-i}) = \frac{(1-t)\,[\theta - (1-\beta)X]}{2\,[1 + b\,[\theta - (1-\beta)X]]} - \frac{b\,[\theta - (1-\beta)X] + \lambda}{2\,[1 + b\,[\theta - (1-\beta)X]]} q_{-i}$$

which is decreasing in the aggregate output by firm i's rivals, q_{-i}. In a symmetric equilibrium, $q_i = q_j$ for all $j \neq i$, yielding a 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 $\pi_i(t) = \frac{(1-t)^2[\theta-(1-\beta)X][1+b(\theta+(1-\beta)X)]}{[2+b(1+N)[\theta-(1-\beta)X]+(N-1)\lambda]^2}$.

Optimal fee. The socially optimal output solves

$$\max_{Q} SW_2(q_i, q_{-i}) = CS_2(Q) + PS_2(q_i, q_{-i}) \tag{4}$$

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. Such a fee, however, would not be credible, i.e., sequentially rational. For the fee to be sequentially rational, it must maximize social welfare from this point forward, and thus coincides with the above program. Solving for socially optimal output Q^{SO}, yields

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

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.[9]

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, β, and in the available stock, θ, for all $\lambda, b \neq 0$.[10] Intuitively, when the resource is more heavily used in the first period and/or more firms compete for it, aggregate appropriation 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, λ, 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

$$\max_{x_i \geq 0} \; \left[1 - b(x_i + X_{-i})\right] x_i - \frac{x_i(x_i + \lambda X_{-i})}{\theta} + \delta \pi_i(t^*) \tag{5}$$

[9] Appendix 1 provides a more detailed analysis of this result.

[10] 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 $\theta > X$ (i.e., exploitation does not 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 since $N \geq 1$.

where $\delta \in [0,1]$ denotes the discount factor. The profit function in problem (5), $\pi_i(t^*)$ —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,

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

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 (5) 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, λ)-pairs, where $\theta = \delta = 1$, $N = 2$ and $\beta = 2/3$. (We consider other parameter values below.)[11]

b	λ	$x_i^*(t^*)$	$x_i^*(0)$	PR
0	1	0.326	0.321	0.005
0.5	1	0.218	0.218	0
1	0.5	0.178	0.180	-0.002
1	0	0.195	0.198	-0.003

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

Specifically, Table I 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 (5) 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, λ)-pairs in Table I, as well as other (b, λ) combinations, and reports the PR next to each point.[12] First, when firms compete in a standard

[11] The numerical evaluation of first-period appropriation $x_i^*(t^*)$ provides two roots. We then evaluate firm i's profits in each root to identify which solution yields the highest profit. In all our numerical simulations, the first (second) root yields a strictly positive (negative) profit thus being a max (min, respectively) of problem (5). A similar argument applies to the equilibrium first-period appropriation without regulation, $x_i^*(0)$, which also yields two roots, where the first one providing the firm with the highest profit under all parameter combinations. See Tables A1-A3 in Appendix 2 for details.

[12] 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. Appendix 2 provides tables listing first-period appropriation with and without regulation in each of these cases, and its associated policy response PR. Appendix 2 also depicts a larger version of Figure 1, where both parameter λ and b in the axis are allowed to exceed 1.

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. When $b = 0$, the first-order condition from problem (5) 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

$$PR = \frac{(N-1)(1-\beta)\delta\theta\lambda(4+3(N-1)\lambda)}{4\left[1+(N-1)\lambda\right]^2\left[2+(N-1)\lambda\right]^3},$$

which is positive since $N \geq 2$ and $\beta \in [0, 1]$ by definition.

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, λ)-pairs with positive PR when the market structure is relatively similar to a standard CPR —low values of b and high values of λ— but a negative PR when firms do not take prices as given.

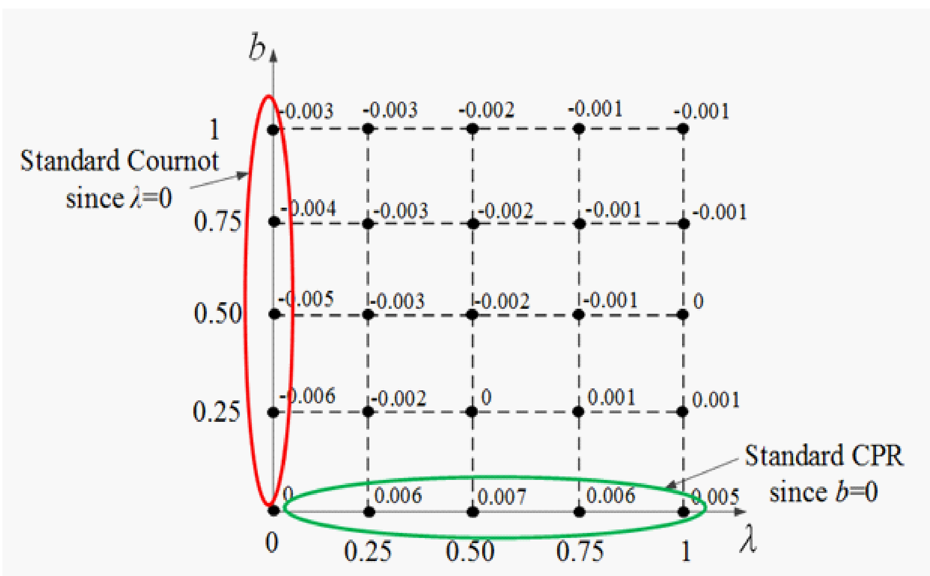

Figure 1. Policy response under different settings.

Intuitively, for a given value of λ, 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 λ) 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 PRs 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, λ)-pairs. Intuitively, a scarcer resource (lower stock θ) leads to a more stringent fee (since t^* and θ move in opposite directions), inducing firms to decrease their first-period appropriation when regulation is present, $x_i(t^*)$, but they reduce their first-period appropriation even more significantly when regulation is absent, $x_i(0)$. As a result, policy response PR becomes positive (negative) under more (less) parameter combinations. Figure 2b confirms this comparative statics by evaluating PR at an scarcer resource ($\theta = 1/3$).

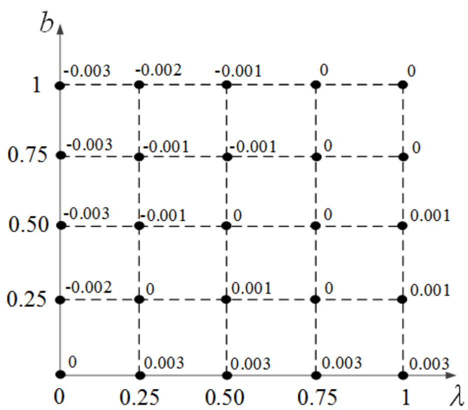

Fig. 2a. PR with θ= 1/2.

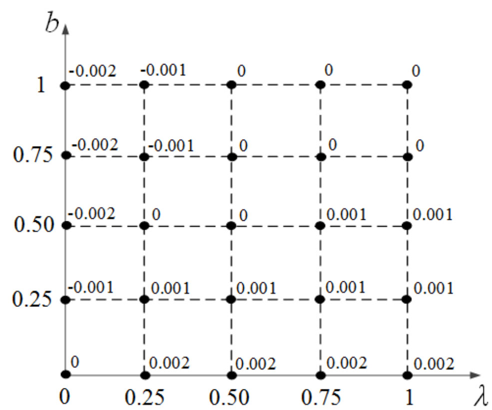

Fig. 2b. PR with θ= 1/3.

Figure 3a illustrates similar findings as in figures 2a-2b when the regeneration rate is smaller, $\beta = 1/3$, since in this case the fee also becomes more stringent. The argument also applies when β further decreases to $\beta = 1/6$.

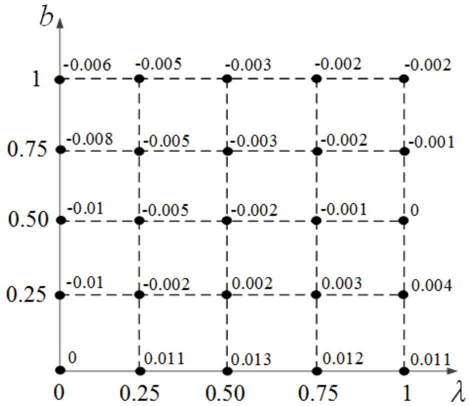

Fig. 3a. PR with $\beta = 1/3$.

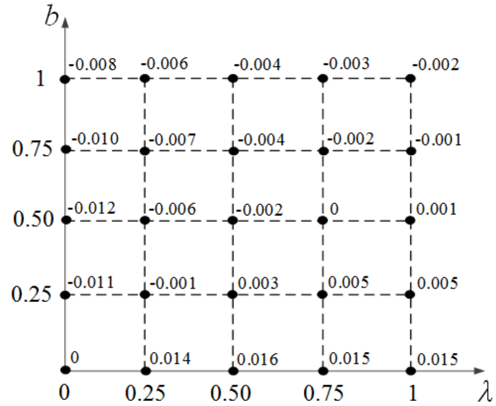

Fig. 3b. PR with $\beta = 1/6$.

Figure 4a reports PRs using the same parameters as Figure 1, but allowing for $N = 3$ firms. Figure 4a shows that PR decreases in absolute value, becoming closer to zero for all (b, λ)-pairs, which occurs both when the PR was positive and when it was negative in Figure 1. Results are emphasized when $N = 4$ firms compete. In fact, when the number of firms competing for the resource increases to $N = 10$ firms, $PR = 0$ for all (b, λ)-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 $x_i^*(t^*) = x_i^*(0)$.

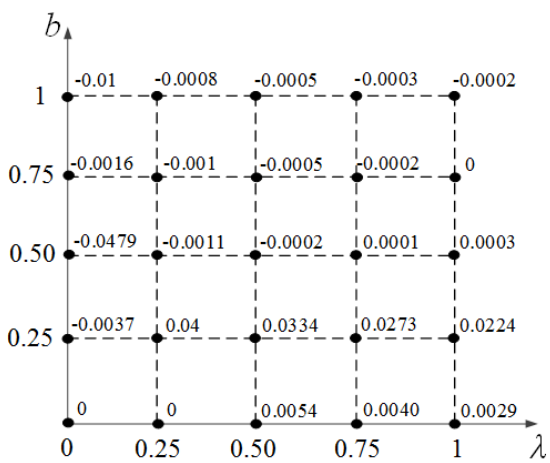

Fig 4a. PR with $N = 3$ firms.

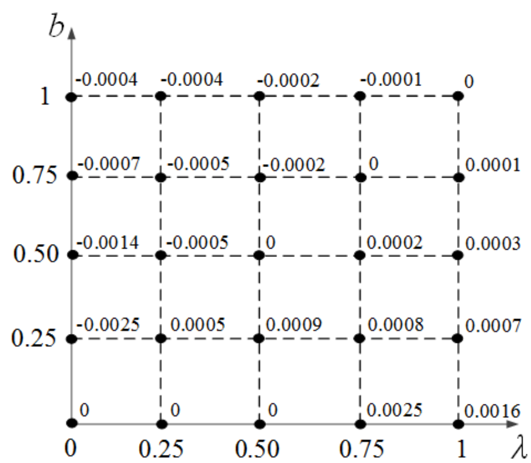

Fig 4b. PR with $N = 4$ firms.

A similar argument applies when firms discount future profits more significantly ($\delta = 1/2$ rather than $\delta = 1$), as depicted in Figure 5. Intuitively, future taxation produces in this setting a smaller change in first-period appropriation, relative to that when taxes are absent. It can be easily shown that further reductions in discount factor δ decrease PR, becoming $PR = 0$ under all (b, λ)-pairs when firms assign no value to future profits, $\delta = 0$.

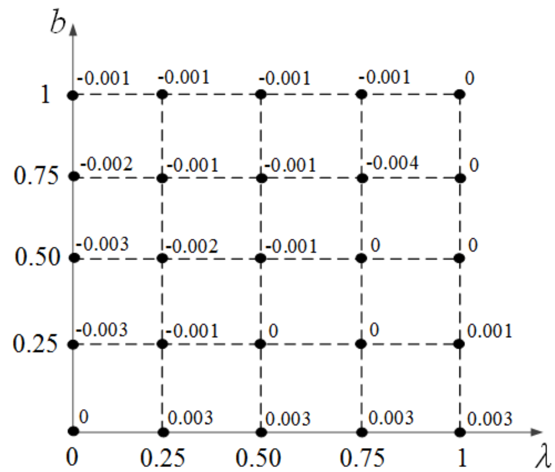

Figure 5. PR with $\delta = 1/2$.

4 Extensions

4.1 Cartel behavior

For completeness, Appendix 3 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,[13] 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, $x_i^C(0)$, 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.

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

b	λ	$x_i^C\left(t^C\right)$	$x_i^C\left(0\right)$	PR^C
0	1	0.1632	0.1527	0.0104
0.5	1	0.1226	0.1201	0.0025
1	0.5	0.1090	0.1086	0.0004
1	0	0.1222	0.1224	−0.0001

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

4.2 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

$$SW_1(x_i, x_{-i}) \equiv CS_1(X) + PS_1(x_i, x_{-i}) - dX^2$$

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

$$SW_2(q_i, q_{-i}) \equiv CS_2(Q) + PS_2(q_i, q_{-i}) - d(Q + \gamma X)^2$$

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 4 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.[14]

b	λ	$x_i^*\left(t^*\right)$	$x_i^*\left(0\right)$	PR with pollution	PR without pollution
0	1	0.327	0.321	0.011	0.005
0.5	1	0.217	0.218	0.003	0
1	0.5	0.175	0.180	0.001	−0.002
1	0	0.191	0.198	0.001	−0.003

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

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 6a, 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 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.

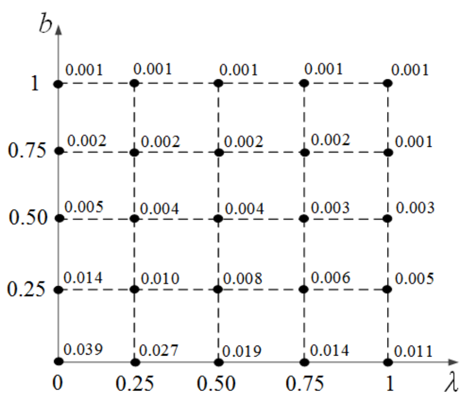

Fig. 6a. PR with environmental damage.

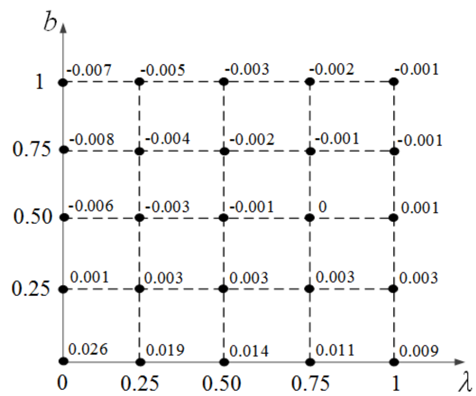

Figure 6b. PR with $\gamma = 1/2$.

Figure 6b reports PR when first-period appropriation generates a larger second-period damage ($\gamma = 1/2$ in figure 6b while $\gamma = 0$ in figure 6a), illustrating that policy response decreases for most parameter combinations, becoming negative (i.e., reduction in first-period appropriation due to future taxes) under larger conditions. Intuitively, this occurs because, as environmental damages persist more significantly over time (higher γ), the regulator sets a more severe tax (see Appendix 4 for more details), which firms anticipate in the first period decreasing their appropriation in this period relative to the setting without regulation.

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, the environmental outcomes are better (negative PRs) if the following characteristics are met when regulation starts: (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 λ), (3) the stock is abundant (relatively high θ), (4) the resource experiences some regeneration across periods (high β), 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.[15] 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 Conclusions

This paper examines how the announcement of a new policy (usage fee) affects firms' appropriation of a common-pool resource. We demonstrate that a lower exploitation of the resource is more likely

[15] 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).

to occur, as anticipation of future taxes, when: (1) competition for the resource is not intense; (2) market prices are not given; (3) cost externalities that firms impose on each other are low; and (4) CPRs are abundant or regeneration of the resource across periods is high. If some of these conditions do not hold, our results indicate that the announcement of future regulations induces firms to increase their first-period appropriation, making overexploitation of the resource more likely.

7 Appendix

7.1 Appendix 1 - Cost externalities

In this appendix we use the second-period social welfare function to illustrate the effect of a marginal increase in q_i in terms of positive and negative externalities. First, we write the social welfare function in this period as follows

$$
\begin{aligned}
SW_2(q_i, q_{-i}) &= CS_2(Q) + PS_2(q_i, q_{-i}) \\
&= \frac{b}{2}(Q)^2 + \sum_i^n \pi\left(q_i, q_{-i}\right) \\
&= \frac{b}{2}(q_i + q_{-i})^2 + \sum_i^n \left\{ \left[1 - b\left(q_i + q_{-i}\right)\right] q_i - \frac{q_i\left(q_i + \lambda q_{-i}\right)}{\theta - (1-\beta)X} \right\} \\
&= \underbrace{\frac{b}{2}(q_i + q_{-i})^2}_{\text{Consumer surplus}} + \underbrace{\left(\left[1 - b\left(q_i + q_{-i}\right)\right] q_i - \frac{q_i\left(q_i + \lambda q_{-i}\right)}{\theta - (1-\beta)X} \right)}_{\text{Firm } i\text{'s profits}} \\
&\quad \underbrace{+ \sum_{j \neq i} \left\{ \left[1 - b\left(q_j + q_i + q_{-j}\right)\right] q_j - \frac{q_j\left(q_j + \lambda\left(q_i + q_{-j}\right)\right)}{\theta - (1-\beta)X} \right\}}_{\text{Profits of firm } i\text{'s rivals}}.
\end{aligned}
$$

Therefore, a marginal increase in firm i's second-period appropriation, q_i, produces: (1) an increase in consumer surplus (first term in the above expression), (2) a change in firm i's profits (second term), and (3) a decrease in the profits of firm i's rivals (third term). The first and second terms capture external effects of a marginal increase in q_i, the former being positive the latter being negative. Overall, in a symmetric outcome, $q_i = q_j = q$, the marginal external effects become

$$bNq - \left[b + \frac{\lambda}{\theta - (1-\beta)X} \right] (N-1)q$$

Solving for λ, this expression is positive if and only if

$$\lambda < \overline{\lambda} \equiv \frac{b\left[(1-\beta)X - \theta\right]}{N-1}.$$

As described in Section 3.1, overall external effects are positive when the positive externality that a marginal increase in q_i generates on consumer surplus dominates the negative externality that q_i imposes on the profits of firm i's rivals (raising their production costs). In this context, optimal regulation leads to a subsidy per unit, $t^* > 0$. When $\lambda = \overline{\lambda}$, the positive consumer surplus externality coincides with the negative cost externality and the optimal policy is a zero fee, $t^* = 0$. Finally, when $\lambda > \overline{\lambda}$, the negative externality dominates and a positive tax $t^* > 0$ is socially optimal.

This result also implies that, starting from a setting where $\lambda > \overline{\lambda}$, a marginal increase in the extent of the cost externality, λ, increases taxes. However, if we start from a setting where $\lambda < \overline{\lambda}$, a marginal increase in λ produces a marginal decrease in the subsidy, until reaching $\lambda = \overline{\lambda}$ where the subsidy collapses to zero, and then becomes a subsidy for all $\lambda > \overline{\lambda}$.

7.2 Appendix 2 - Additional figures and tables

Figure 1' below depicts a larger version of Figure 1 in the main body of the text, but allowing for values of the cost externality parameter, λ, to exceed 1, and for values of the slope of the inverse demand curve, b, to exceed 1. The results are unaffected. In particular, (b, λ)-pairs where b is relatively low yield positive policy responses PR, while pairs where b is relatively high produce negative policy responses. Graphically, the PR takes larger positive values when we move to (b, λ)-pairs in the southeast of the figure, but takes more negative values when we move to (b, λ)-pairs in the northwest of the figure.

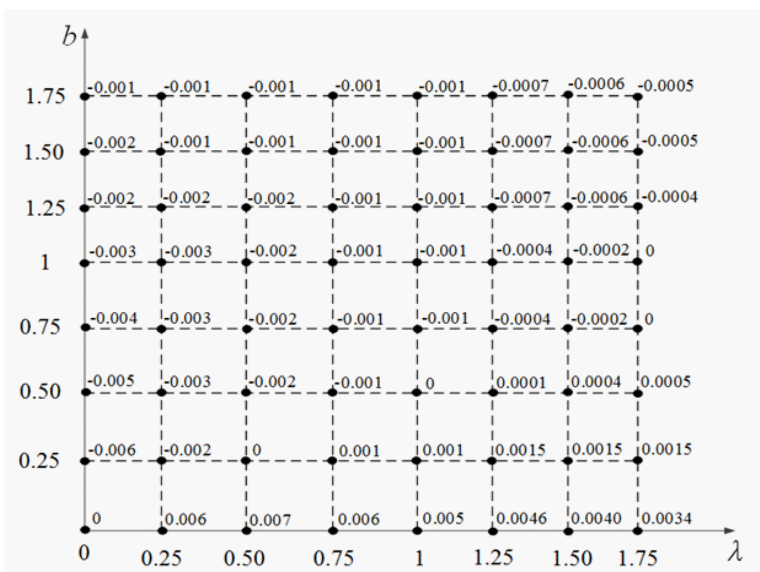

Figure 1'. Policy response under larger values of λ and b.

The following tables report the PR for each (b, λ)-pair in Figures 1, 2a, 3a, and 4a, respectively. For completeness, we provide all the root/s of first-period appropriation for each vector of parameter values, $x_1(t^*)$ and $x_2(t^*)$, as well as its corresponding profits, $\pi_1(t^*)$ and $\pi_2(t^*)$, which helps us identify which root yields the highest profit for firm i under regulation, and thus becomes the solution to problem (5) in the main body of the paper. We then report first-period appropriation roots under no regulation, $x_1(0)$ and $x_2(0)$, and their associated profits, $\pi_1(0)$ and $\pi_2(0)$. The last column reports the policy response $PR = x_1(t^*) - x_1(0)$. When aggregate first-period appropriation exceeds the total stock (as in Table A3), we assume that aggregate exploitation coincides with the available first-period stock, θ. Table A1 also includes the equilibrium tax t^* evaluated at each parameter values.

		Regulation				No regulation				Policy response	Tax
b	λ	$x_1(t^*)$	$\pi_1(t^*)$	$x_2(t^*)$	$\pi_2(t^*)$	$x_1(0)$	$\pi_1(0)$	$x_2(0)$	$\pi_2(0)$	PR	t^*
0	0	0.458	0.422			0.458	0.422			0	0
0	0.25	0.421	0.315			0.415	0.343			0.006	0.100
0	0.5	0.385	0.245			0.378	0.283			0.007	0.167
0	0.75	0.354	0.197			0.348	0.238			0.006	0.214
0	1	0.326	0.162			0.321	0.202			0.005	0.250
0.25	0	0.342	0.328			0.348	0.304	6.093	-57.76	-0.006	-0.081
0.25	0.25	0.319	0.253	8.303	-101.09	0.321	0.257	6.523	-75.91	-0.002	0.018
0.25	0.5	0.298	0.204	9.605	-153.61	0.298	0.220	6.940	-96.38	0.000	0.088
0.25	0.75	0.278	0.168	10.981	-228.54	0.277	0.191	7.327	-117.65	0.001	0.140
0.25	1	0.261	0.142	12.391	-328.14	0.260	0.167			0.001	0.180
0.5	0	0.274	0.269			0.279	0.234	3.821	-28.78	-0.005	-0.145
0.5	0.25	0.258	0.214	4.866	-44.23	0.261	0.204	4.0358	-35.82	-0.003	-0.049
0.5	0.5	0.243	0.176	5.5	-62.13	0.245	0.179	4.24	-43.440	-0.002	0.021
0.5	0.75	0.230	0.148	6.174	-86.86	0.231	0.159	4.429	-50.96	-0.001	0.075
0.5	1	0.218	0.127	6.867	-118.75	0.218	0.142			0.000	0.118
0.75	0	0.228	0.228			0.232	0.188	3.050	-22.40	-0.004	-0.194
0.75	0.25	0.216	0.186	3.738	-32.10	0.219	0.168	3.193	-26.91	-0.003	-0.104
0.75	0.5	0.206	0.156	4.155	-42.77	0.208	0.150	3.331	-31.65	-0.002	-0.034
0.75	0.75	0.196	0.133	4.599	-57.08	0.197	0.136	3.456	-36.21	-0.001	0.020
0.75	1	0.187	0.116	5.057	-75.04	0.188	0.123			-0.001	0.065
1	0	0.195	0.197			0.198	0.157	2.661	-20.27	-0.003	-0.233
1	0.25	0.186	0.164	3.178	-27.72	0.189	0.142	2.770	-23.71	-0.003	-0.147
1	0.5	0.178	0.140	3.489	-35.59	0.180	0.129	2.873	-27.29	-0.002	-0.080
1	0.75	0.171	0.121	3.820	-45.79	0.172	0.118	2.967	-30.68	-0.001	-0.026
1	1	0.164	0.107	4.161	-58.37	0.165	0.108			-0.001	0.019

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

		Regulation				No regulation				
b	λ	$x_1(t^*)$	$\pi_1(t^*)$	$x_2(t^*)$	$\pi_2(t^*)$	$x_1(0)$	$\pi_1(0)$	$x_2(0)$	$\pi_2(0)$	PR
0	0	0.229	0.211			0.229	0.211			0
0	0.25	0.210	0.157			0.207	0.171			0.003
0	0.5	0.193	0.123			0.190	0.142			0.003
0	0.75	0.177	0.099			0.174	0.119			0.003
0	1	0.163	0.081			0.160	0.101			0.003
0.25	0	0.196	0.184			0.198	0.178	5.267	-75.225	-0.002
0.25	0.25	0.181	0.140			0.181	0.147	5.703	-103.101	0
0.25	0.5	0.168	0.111	8.988	-242.004	0.167	0.124	6.130	-135.656	0.001
0.25	0.75	0.156	0.090	10.389	-374.020	0.155	0.106	6.533	-171.151	0.001
0.25	1	0.145	0.076	11.819	-552.047	0.144	0.091			0.001
0.5	0	0.171	0.164			0.174	0.152	3.047	-28.874	-0.003
0.5	0.25	0.160	0.127	4.151	-50.558	0.161	0.129	3.261	-37.964	-0.001
0.5	0.5	0.149	0.102	4.803	-76.793	0.149	0.110	3.470	-48.190	0
0.5	0.75	0.139	0.084	5.491	-114.259	0.139	0.095	3.663	-58.836	0
0.5	1	0.131	0.071	6.195	-164.085	0.130	0.084			0.001
0.75	0	0.152	0.148			0.155	0.132	2.292	-18.497	-0.003
0.75	0.25	0.143	0.116	3.002	-29.970	0.144	0.114	2.435	-23.579	-0.001
0.75	0.5	0.134	0.094	3.429	-43.598	0.135	0.099	2.573	-29.174	-0.001
0.75	0.75	0.126	0.079	3.883	-62.721	0.126	0.087	2.669	-34.825	0
0.75	1	0.119	0.067	4.348	-87.771	0.119	0.077			0
1	0	0.137	0.134			0.140	0.117	1.910	-14.394	-0.003
1	0.25	0.129	0.107	2.433	-22.116	0.131	0.102	2.018	-17.906	-0.002
1	0.5	0.122	0.088	2.75	-31.063	0.123	0.090	2.121	-21.714	-0.001
1	0.75	0.115	0.074	3.087	-43.430	0.115	0.080	2.215	-25.473	0
1	1	0.109	0.064	3.434	-59.364	0.109	0.071			0

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

		Regulation				No regulation				
b	λ	$x_1(t^*)$	$\pi_1(t^*)$	$x_2(t^*)$	$\pi_2(t^*)$	$x_1(0)$	$\pi_1(0)$	$x_2(0)$	$\pi_2(0)$	PR
0	0	0.417	0.354			0.417	0.354			0
0	0.25	0.397	0.275			0.386	0.296			0.011
0	0.5	0.370	0.221			0.357	0.250			0.013
0	0.75	0.344	0.181			0.332	0.213			0.012
0	1	0.319	0.151			0.308	0.220			0.011
0.25	0	0.317	0.292			0.327	0.276	3.214	-15.007	-0.01
0.25	0.25	0.303	0.230	3.970	-21.090	0.305	0.236	3.406	-19.359	-0.002
0.25	0.5	0.287	0.187	4.554	-30.610	0.285	0.204	3.586	-23.964	0.002
0.25	0.75	0.271	0.157	5.200	-45.558	0.268	0.178	3.742	-27.945	0.003
0.25	1	0.256	0.133	5.876	-66.176	0.252	0.157			0.004
0.5	0	0.259	0.248			0.269	0.221	2.003	-7.096	-0.01
0.5	0.25	0.247	0.199			0.252	0.193	2.097	-8.726	-0.005
0.5	0.5	0.235	0.165	2.612	-12.206	0.237	0.170	2.185	-10.356	-0.002
0.5	0.75	0.224	0.140	2.923	-16.994	0.225	0.151	2.257	-11.617	-0.001
0.5	1	0.214	0.120	3.251	-23.429	0.214	0.135			0
0.75	0	0.219	0.215			0.227	0.182			-0.008
0.75	0.25	0.209	0.176	1.802	-6.663	0.214	0.162	1.651	-6.425	-0.005
0.75	0.5	0.200	0.148	1.983	-8.471	0.203	0.145	1.710	-7.417	-0.003
0.75	0.75	0.191	0.127	2.186	-11.228	0.193	0.131	1.757	-8.148	-0.002
0.75	1	0.184	0.110	2.401	-14.834	0.185	0.119			-0.001
1	0	0.189	0.189			0.195	0.153	1.377	-4.843	-0.006
1	0.25	0.181	0.157	1.539	-5.810	0.186	0.138	1.426	-5.614	-0.005
1	0.5	0.174	0.134	1.673	-7.145	0.177	0.126	1.470	-6.359	-0.003
1	0.75	0.167	0.116	1.824	-9.123	0.169	0.115	1.506	-6.892	-0.002
1	1	0.161	0.102	1.984	-11.651	0.163	0.106			-0.002

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

		Regulation				No regulation				
b	λ	$x_1(t^*)$	$\pi_1(t^*)$	$x_2(t^*)$	$\pi_2(t^*)$	$x_1(0)$	$\pi_1(0)$	$x_2(0)$	$\pi_2(0)$	PR
0	0	0.25	0.354			0.25	0.354			0
0	0.25	0.25	0.195			0.25	0.228			0
0	0.5	0.25	0.120			0.25	0.148			0
0	0.75	0.233	0.073			0.231	0.096			0.0025
0	1	0.199	0.052			0.197	0.071			0.0016
0.25	0	0.296	0.223	2.586	-15.52	0.299	0.212	2.256	-11.77	-0.0025
0.25	0.25	0.2454	0.125	3.568	-34.88	0.2449	0.141	2.663	-21.65	0.0005
0.25	0.5	0.208	0.083	4.255	-51.74	0.207	0.101	3.068	-35.20	0.0009
0.25	0.75	0.181	0.059	5.296	-97.67	0.180	0.076	3.463	-52.19	0.0008
0.25	1	0.1592	0.045	6.376	-170.5	0.1585	0.059			0.0007
0.5	0	0.219	0.157	1.675	-8.913	0.220	0.142	1.507	-7.132	-0.0014
0.5	0.25	0.188	0.097	2.167	-16.79	0.189	0.103	1.715	-11.42	-0.0005
0.5	0.5	0.1652	0.068	2.490	-22.55	0.1652	0.165	1.918	-16.86	0.0000
0.5	0.75	0.1472	0.051	3.002	-38.16	0.1470	0.062	2.115	-23.19	0.0002
0.5	1	0.133	0.039	3.536	-61.70	0.1327	0.051			0.0003
0.75	0	0.172	0.120	1.365	-7.580	0.173	0.104	1.252	-6.300	-0.0007
0.75	0.25	0.1525	0.078	1.695	-12.84	0.1530	0.080	1.393	-9.240	-0.0005
0.75	0.5	0.1370	0.058	1.908	-16.31	0.1372	0.064			-0.0002
0.75	0.75	0.1243	0.0445	2.2462	-25.56	0.1243	0.0526	1.661	-16.74	0.0000
0.75	1	0.1138	0.0356	2.5996	-38.92	0.1137	0.0439			0.0001
1	0	0.1422	0.0945	1.2088	-7.29	0.1426	0.0810	1.124	-6.22	-0.0004
1	0.25	0.1282	0.0663	1.4584	-11.45	0.1286	0.0654	1.231	-8.59	-0.0004
1	0.5	0.1170	0.0502	1.6181	-14.07	0.1172	0.0540	1.335	-11.33	-0.0002
1	0.75	0.1076	0.0398	1.8709	-20.79	0.1077	0.0454	1.434	-14.32	-0.0001
1	1	0.0996	0.0325	2.1348	-30.18	0.0996	0.0496			0.0000

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

7.3 Appendix 3 - 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

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

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 (4) 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.

7.4 Appendix 4 - 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 (3), 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 (4), but including the environmental damage from appropriation, as follows

$$\max_{Q} SW_2(q_i, q_{-i}) = CS_2(Q) + PS_2(q_i, q_{-i}) - d(Q + \gamma X)^2 \tag{A3}$$

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

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

When environmental damages are absent, $d = 0$, this expression simplifies to the socially optimal output we found in Section 3.1

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. Solving for tax t, yields

$$t^* = \frac{4dX\gamma + 2dN\left[\theta - (1-\beta)X\right] + b(2d(N+1)X\gamma)(\theta - (1-\beta)X - 1) + (N-1)(2N - 1 + 2dX\gamma)\lambda}{2 + (b+2d)N\left[\theta - (1-\beta)X\right] + (N-1)2N\lambda}$$

Differentiating the optimal emission fee t^* with respect to γ, we find

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

which is positive since, in the numerator, term $\left[\theta - (1-\beta)X\right] + (N-1)\lambda$ is positive because $\theta > X(\beta - 1)$ and $(N-1)\lambda \geq 0$. 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

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

which is positive since, in the numerator, $\theta > X(\beta - 1)$, and $(N-1)\lambda \geq 0$ and $2NX\gamma\lambda(N-1) \geq 0$, implying that the numerator is positive. The denominator is squared so it is also 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

$$\max_{x_i \geq 0} \quad \left[1 - b(x_i + X_{-i})\right] x_i - \frac{x_i(x_i + \lambda X_{-i})}{\theta} + \delta\pi_i(t^*) \tag{A4}$$

which is analogous to problem (5) 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,

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

Differentiating problem (A4) 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.

7.5 Appendix 5 - Alternative stock regeneration

In this appendix, we examine how our results in Sections 3.1 and 3.2 are affected when we consider an alternative stock regeneration function, where the available stock at the beginning of the second period is defined as $\theta(1+g)-X$, where $g \geq 0$ denotes the growth rate of the initial stock. As in those sections, we solve the sequential-move game by backward induction.

7.5.1 Second stage

Second-period appropriation. In the second period, every firm i solves

$$\pi_i(t) \equiv \max_{q_i \geq 0} \; [1 - b\,(q_i + q_{-i})]\, q_i - \frac{q_i(q_i + \lambda q_{-i})}{\theta(1+g) - X} - tq_i$$

Differentiating with respect to output q_i and solving, we obtain the best response function

$$q_i(q_{-i}) = \frac{(1-t)\,[(1+g)\theta - X]}{2\,[1 + b\,[(1+g)\theta - X]]} - \frac{b\,[(1+g)\theta - X] + \lambda}{2\,[1 + b\,[(1+g)\theta - X]]} q_{-i}$$

which is decreasing in the aggregate output by firm i's rivals, q_{-i}. In a symmetric equilibrium, $q_i = q_j$ for all $j \neq i$, yielding a profit-maximizing output

$$q_i(t) = \frac{(1-t)\,[(1+g)\theta - X]}{2 + b(N+1)\,[(1+g)\theta - X] - (N-1)\lambda}$$

which yields second-period profits of $\pi_i(t) = \pi_i(t) = \frac{(1-t)^2[(1+g)\theta - X][1+b[(1+g)\theta - X]]}{[2+b(N+1)[(1+g)\theta - X]-(N-1)\lambda]^2}$.

Optimal fee. The socially optimal output solves

$$\max_{Q} SW_2(q_i, q_{-i}) = CS_2(Q) + PS_2(q_i, q_{-i})$$

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

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

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

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

This emission fee is positive if $b = 0$ and $\lambda > 0$ (as in standard CPR models). In contrast, the fee becomes negative (that is, a production subsidy) when $b > 0$ and $\lambda = 0$ (as in standard Cournot models).

7.6 First period

In the first period, every firm i solves

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

where $\delta \in [0, 1]$ denotes the discount factor. The profit function in the above profit-maximization problem, $\pi_i(t^*)$ —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,

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

Differentiating with respect to first-period appropriation, x_i, in the above profit-maximization problem yields a highly non-linear equation which does not allow for an analytical expression of $x_i^*\,(t^*)$. Table A5 numerically evaluates $x^*\,(t^*)$ at the same parameter values as Table I in the main body of the paper.

b	λ	$x_i^*\,(t^*)$	$x_i^*\,(0)$	PR
0	1	0.313	0.296	0.017
0.5	1	0.210	0.213	−0.003
1	0.5	0.173	0.178	−0.005
1	0	0.190	0.197	−0.007

Table A4. Policy response under alternative regeneration.

Figure A1 depicts the policy response PR under the same parameter conditions as figure 1 in section 3.2 of the paper. Responses are qualitatively unaffected, although they become more negative in markets with a Cournot structure (low λ but positive b) and relatively more positive in CPRs (positive λ but low b), although the differences with figure 1 are extremely small.

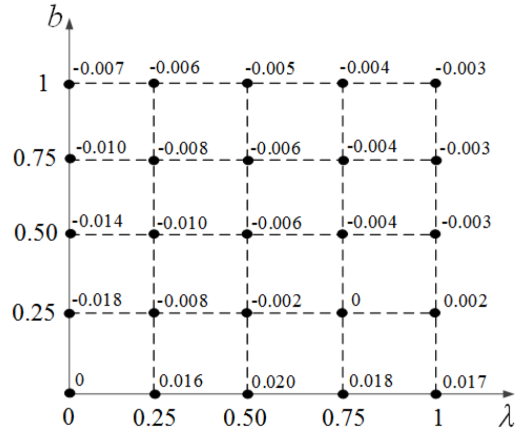

Figure A1. Policy reponse PR.

Figure A2a and A2b illustrate the policy response under the same parameter values as figures 2a and 2b in section 3.3 in the paper. As in figure A1, policy responses are qualitative unaffected, although they are slightly larger in absolute value than in figures 2a and 2b.

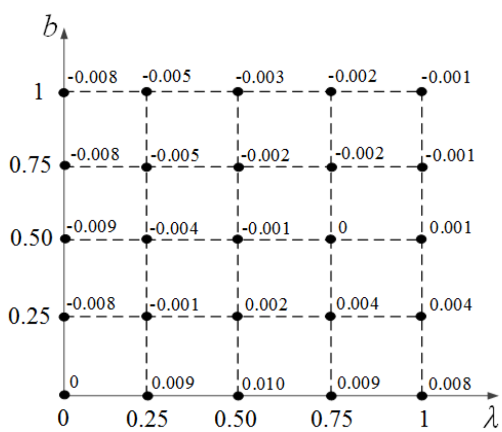

Figure A2a. PR with $\theta = 1/2$.

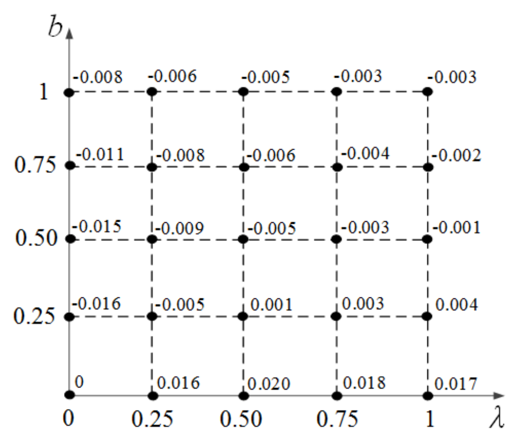

Figure A2a. PR with $\beta = 1/3$.

7.7 Appendix 6 - Allowing for asymmetric firms

In this appendix, we examine how our results in Sections 3.1 and 3.2 are affected when we assume that firms are asymmetric in their production costs. In particular, we consider that firm i's costs are still given by $\frac{x_i(x_i+\lambda x_j)}{\theta}$ while firm j's are $\alpha\frac{x_i(x_i+\lambda x_j)}{\theta}$, where parameter $\alpha \in [0,1]$ represents firm j's cost advantage relative to firm i. When $\alpha = 1$, firm i and j exhibit the same cost function, as in the main body of the paper, while when $\alpha < 1$ firm j benefits from a cost advantage. A similar argument applies to second-period costs.

7.7.1 Second stage

Second-period appropriation. In the second period, every firm i solves

$$\pi_i(t) \equiv \max_{q_i \geq 0} \left[1 - b\left(q_i + q_j\right)\right] q_i - \frac{q_i(q_i + \lambda q_j)}{\theta - (1-\beta)X} - tq_i \tag{A5}$$

and similarly for firm j, which solves

$$\pi_j(t) \equiv \max_{q_j \geq 0} \left[1 - b\left(q_i + q_{-i}\right)\right] q_j - \alpha\frac{q_j(q_j + \lambda q_i)}{\theta - (1-\beta)X} - tq_j. \tag{A6}$$

Differentiating with respect to output q_i in A5, with respect to output q_j in A6, and simultaneously solving for q_i and q_j, we obtain

$$\begin{aligned} q_i(t) &= \frac{(1-t)\left[\theta - (1-\beta)X\right]\left[2\alpha - \lambda + b\left[\theta - (1-\beta)X\right]\right]}{3b^2\left[\theta - (1-\beta)X\right]^2 + b(4-\lambda)(1+\alpha)\left[\theta - (1-\beta)X\right] + \alpha(4-\lambda^2)}, \text{ and} \\ q_j(t) &= \frac{(1-t)\left[\theta - (1-\beta)X\right]\left[2 - \alpha\lambda + b\left[\theta - (1-\beta)X\right]\right]}{3b^2\left[\theta - (1-\beta)X\right]^2 + b(4-\lambda)(1+\alpha)\left[\theta - (1-\beta)X\right] + \alpha(4-\lambda^2)}. \end{aligned}$$

In the case that firms face symmetric costs, $\alpha = 1$, the above equilibrium outputs collapse to

$$q_i(t) = q_j(t) = \frac{(1-t)\left[\theta - (1-\beta)X\right]}{2 + 3b\left[\theta - (1-\beta)X\right] + \lambda},$$

which coincides with our equilibrium output in Section 3.1, evaluated at $N = 2$ firms. Second-period profits for firm i are,

$$\pi_i(t) = \frac{(1-t)^2\left[\theta - (1-\beta)X\right]\left[1 + b(\theta - (1-\beta)X)\right]\left[2\alpha - \lambda + b\left[\theta - (1-\beta)X\right]\right]^2}{\left[3b^2\left[\theta - (1-\beta)X\right]^2 + b(4-\lambda)(1+\alpha)\left[\theta - (1-\beta)X\right] + \alpha(4-\lambda^2)\right]^2}$$

while those of firm j are.

$$\pi_j(t) = \frac{(1-t)^2\left[\theta - (1-\beta)X\right]\left[\alpha + b(\theta - (1-\beta)X)\right]\left[2 - \alpha\lambda + b\left[\theta - (1-\beta)X\right]\right]^2}{\left[3b^2\left[\theta - (1-\beta)X\right]^2 + b(4-\lambda)(1+\alpha)\left[\theta - (1-\beta)X\right] + \alpha(4-\lambda^2)\right]^2}.$$

Optimal fee. The socially optimal output solves

$$\max_{q_i, q_j} SW_2(q_i, q_j) = CS_2(q_i, q_j) + PS_2(q_i, q_j) \tag{A7}$$

where $CS_2(q_i, q_j) = \frac{1}{2}b(q_i + q_j)^2$ denotes second-period consumer surplus, and producer surplus is

$$PS_2(q_i, q_j) = \left([1 - b\,(q_i + q_j)]\, q_i - \frac{q_i(q_i + \lambda q_j)}{\theta - (1-\beta)X} \right) + \left([1 - b\,(q_i + q_{-i})]\, q_j - \alpha \frac{q_j(q_j + \lambda q_i)}{\theta - (1-\beta)X} \right).$$

Differentiating problem (A7) with respect to q_i and q_j, and then simultaneously solving for q_i and q_j, we find socially optimal output levels for each firm

$$\begin{aligned} q_i^{SO} &= \frac{[\theta - (1-\beta)X]\,[\alpha(2-\lambda) - \lambda]}{4\alpha + 2b(1+\alpha)(1-\lambda)\,[\theta - (1-\beta)X] - (1+\alpha)^2\lambda^2}, \text{ and} \\ q_j^{SO} &= \frac{[\theta - (1-\beta)X]\,[2 - \lambda(1+\alpha)]}{4\alpha + 2b(1+\alpha)(1-\lambda)\,[\theta - (1-\beta)X] - (1+\alpha)^2\lambda^2}. \end{aligned}$$

In the case that firms face symmetric costs, $\alpha = 1$, the above socially optimal output collapse to

$$q_i^{SO} = q_j^{SO} = \frac{\theta - (1-\beta)X}{2\,[1 + \lambda + b\,[\theta - (1-\beta)X] + \lambda]},$$

which coincides with our results in Section 3.1, i.e., $q_i^{SO} = \frac{Q^{SO}}{N}$, when evaluated at $N = 2$ firms.

Therefore, the optimal fee t_i^* for firm i solves $q_i^{SO} = q_i(t)$, as found above. A similar argument applies for firm j. For compactness, we do not include here the expression of the optimal fees, but they can be provided by the authors upon request.

7.7.2 First period

In the first period, every firm i solves

$$\max_{x_i \geq 0} \quad [1 - b(x_i + x_j)]\, x_i - \frac{x_i(x_i + \lambda x_j)}{\theta} + \delta \pi_i(t_i^*) \tag{A8}$$

where $\delta \in [0, 1]$ denotes the discount factor. The profit function in problem (A8), $\pi_i(t_i^*)$ —the value function of firm i's second-period problem— is evaluated at the optimal fee t_i^* found above, since the firm can anticipate the fee effective in the subsequent stage of the game, that is,

$$\pi_i(t_i^*) = \frac{[\theta - (1-\beta)(x_i + x_j)]\,[1 + b(\theta - (1-\beta)(x_i + x_j))]\,[\alpha(2-\lambda) - \lambda]^2}{\left[4\alpha + 2b(1+\alpha)(1-\lambda)\,[\theta - (1-\beta)(x_i + x_j)] - (1+\alpha)^2\lambda^2\right]^2}.$$

A similar argument applies for firm j, which solves

$$\max_{x_j \geq 0} \quad [1 - b(x_i + x_j)]\, x_j - \alpha \frac{x_j(x_j + \lambda x_i)}{\theta} + \delta \pi_j(t_j^*) \tag{A9}$$

where $\pi_j(t_j^*)$ denotes firm j's value function in the second-period problem, which simplifies to

$$\pi_j(t_j^*) = \frac{[\theta - (1-\beta)(x_i + x_j)]\,[\alpha + b(\theta - (1-\beta)(x_i + x_j))]\,[2 - \lambda(1+\alpha)]^2}{\left[4\alpha + 2b(1+\alpha)(1-\lambda)\,[\theta - (1-\beta)(x_i + x_j)] - (1+\alpha)^2\lambda^2\right]^2}.$$

Differentiating problem (A8) with respect to firm i's first-period appropriation, x_i, differentiating (A9) with respect to firm j's first-period appropriation, x_j, and simultaneously solving for x_i and x_j, yields a highly non-linear equation which does not allow for an analytical expression of $x_i^*(t_i^*)$ and $x_j^*\left(t_j^*\right)$. Table A5 numerically evaluates the first-order conditions of A8 and A9, before simultaneously solving for equilibrium first-period appropriation levels for each firm. For comparison purposes, we consider the same parameter values as in previous tables where $\theta = \delta = 1$, $N = 2$ and $\beta = 2/3$. For completeness, we separately report firm i's policy response, $PR_i = x_i(t_i^*) - x_i(0)$, firm j's, $PR_j = x_j(t_j^*) - x_j(0)$, and the aggregate policy response, $PR = \left[x_i(t_i^*) + x_j(t_j^*)\right] - [x_i(0) + x_j(0)]$.

		Regulation		No regulation				
b	λ	$x_i(t_i^*)$	$x_j(t_j^*)$	$x_i(0)$	$x_j(0)$	PR_i	PR_j	PR
0	0	0.50	0.50	0.50	0.50	0	0	0
0	0.25	0.50	0.50	0.50	0.50	0	0	0
0	0.5	0.50	0.50	0.50	0.50	0	0	0
0	0.75	0.50	0.50	0.50	0.50	0	0	0
0.25	0	0.329	0.533	0.327	0.588	0.002	-0.055	-0.053
0.25	0.25	0.286	0.525	0.273	0.580	0.012	-0.055	-0.043
0.25	0.5	0.245	0.509	0.218	0.581	0.027	-0.073	-0.046
0.25	0.75	0.226	0.428	0.158	0.593	0.068	-0.165	-0.097
0.5	0	0.259	0.394	0.256	0.426	0.003	-0.003	-0.029
0.5	0.25	0.232	0.386	0.222	0.422	0.010	-0.036	-0.026
0.5	0.5	0.207	0.374	0.218	0.581	-0.011	-0.207	-0.218
0.5	0.75	0.198	0.322	0.151	0.428	0.047	-0.106	-0.059
0.75	0	0.215	0.312	0.211	0.332	0.003	-0.020	-0.017
0.75	0.25	0.195	0.306	0.188	0.329	0.007	-0.023	-0.016
0.75	0.5	0.179	0.297	0.165	0.329	0.014	-0.032	-0.018
0.75	0.75	0.173	0.262	0.140	0.332	0.033	-0.071	-0.038

Table A5. First-period appropriation and policy responses when firms are cost asymmetric.

Table A5 indicates that: (1) the most efficient company (firm j) exploits the resource more intensively than its relatively less efficient rival (firm i); and (2) that firm j exhibits a negative policy response ($PR_j < 0$, thus reducing its appropriation after taxes are introduced) under large parameter conditions. Its less efficient rival, however, sustains a positive policy response, $PR_i > 0$, under relatively general parameter combinations. Overall, the negative policy response of the relatively efficient firm tends to dominate, yielding a negative policy response under large conditions.

References

[1] Agnolucci, P. and P. Ekins (2004) "The announcement effect and environmental taxation," Tyndall Centre Working Paper 53, Tyndall Centre for Climate Change Research.

[2] Costello, C. and D. Kaffine (2008) "Natural resource use with limited-tenure property rights," Journal of Environmental Economics and Management, 55(1), pp. 20-36.

[3] Di Maria, C., S. Smulders, and E. Van der Werf (2012) "Absolute abundance and relative scarcity: Environmental policy with implementation lags," Ecological Economics, 74, pp. 104–119.

[4] Di Maria, C., I. Lange, and E. van der Werf (2014) "Should we be worried about the green paradox? Announcement effects of the Acid Rain Program," European Economic Review, 69, pp. 143-162.

[5] Di Maria, C., I. Lange and E. van der Werf (2014) "Going full circle: demand-side constraints to the green paradox," Chapter 10 in Karen Pittel, Frederick van der Ploeg and Cees Withagen (eds.), *Climate Policy and Exhaustible Resources – The Green Paradox and Beyond.* Cambridge: MIT Press

[6] FAO (2018) "The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals." Rome

[7] Grafton, Q., T. Kompas (2012) "Substitution Between Biofuels and Fossil Fuels: Is there a Green Paradox?" Journal of Environmental Economics and Management, 64, pp. 328-341.

[8] Hammar, H., and Å. Löfgren (2001) "The determinants of sulphur emissions from oil consumption in Swedish manufacturing industry 1976–1995," The Energy Journal, 22 (2), pp. 107-126.

[9] Hoel, M. (2010) "Is there a Green Paradox?" CESifo Working Paper Series No. 3168.

[10] Jensen, S., K. Mohlin, K. Pittel, and T. Sterner (2015) "An introduction to the green paradox: The unintended consequences of climate policies," Review of Environmental Economics and Policy, 9(2), pp. 246–265.

[11] Lemoine, D. (2017) "Green expectations: current effects of anticipated carbon pricing," Review of Economics and Statistics, 99(3), pp. 499-513.

[12] Malik, A.S, and A.A. Elrod (2017) "The effect of environmental regulation on plant level product mix: A study of EPA's Cluster rule," Journal of Environmental Economics and Management, 83, pp. 164-184.

[13] Marz, W. and J. Pfeiffer (2015) "Carbon Taxes, Oil Monopoly and Petrodollar Recycling," Ifo Working Paper 204, September.

[14] Nachtigall, D. and D. Rubbelke (2016) “The Green Paradox and Learning-by-Doing in the Renewable Energy Sector,” Resource and Energy Economics, 43, pp. 74-92.

[15] Riekhof, M. and J. Bröcker (2017) “Does The Adverse Announcement Effect Of Climate Policy Matter?—A Dynamic General Equilibrium Analysis,” Climate Change Economics, 8(2), pp. 1-34.

[16] Sinn, H.-W. (2008) “Public policies against global warming: a supply side approach,” International Tax and Public Finance, 15(4), pp. 360–394.

[17] Smulders, S., Y. Tsur, and A. Zemel (2012) “Announcing Climate Policy: Can a green paradox arise without Scarcity?” Journal of Environmental Economics and Management. 64(3), pp 364-376.

[18] Strand, J. (2007) “Technology Treaties And Fossil-Fuels Extraction,” Energy Journal, 28(4), pp. 129–141.

[19] Swedish Environmental Protection Agency (2000) “The Swedish charge on nitrogen oxides-cost effective emission reduction.”

[20] Van der Ploeg, F. and C. Withagen (2012) “Is there really a Green Paradox?” Journal of Environmental Economics and Management, 64, pp. 342-363.

[21] Van Der Ploeg, F. (2013) “Cumulative Carbon Emissions And The Green Paradox,” Annual Review of Resource Economics, 5, pp. 281-300.

[22] Werf, E. van der, and C. Di Maria (2011) “Unintended detrimental effects of environmental policy: the green paradox and beyond,” CESifo Working Paper, 3466.