When Does the Green Paradox Fail?
The Anticipatory Effects of Taxation

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Abstract

This paper shows that, after the announcement of a new environmental policy, firms can respond increasing or decreasing their appropriation and pollution. In addition, we demonstrate that reductions in exploitation levels are more significant when: (1) few firms compete for the resource; (2) firms are not price takers; (3) firms do not impose significant cost externalities on each other; and (4) the resource is abundant. Our results, therefore, indicate that policy announcements can trigger a reduction in resource exploitation before the law comes into effect, helping rationalize empirical observations.

KEYWORDS: Green paradox; Decrease in Exploitation; Environmental policy.
JEL CLASSIFICATION: H23; L13; Q5.

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1 Introduction

The "green paradox" states that, after the announcement of an environmental policy, such as the imposition of an emission fee, firms exploiting a common pool resource (CPR) respond by increasing their appropriation before the law comes into effect.[1] Intuitively, firms seek to maximize their current profits anticipating a loss in future payoffs once regulation comes into force. Most studies empirically supporting the green paradox focus on firms exploiting natural resources.[2] Other papers found, however, 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 percent reduction in sulphur dioxide between its announcement, in 1989, and its final implementation, in 1992.[3]

The green paradox has been extensively studied in the extraction of fossil fuels, considering how subsidies on biofuels —or a cheaper renewable backstop technology— can increase current fossil fuel exploitation; see, for instance, Grafton et al. (2012) and Van der Ploeg and Withagen (2012). We consider, however, an industry with N firms exploiting a CPR which does not have a close substitute; implying that the regulator cannot subsidize a clean alternative to affect CPR exploitation. Our setting allows for different types of industries as special cases. First, when firms are price takers in the market where they sell their appropriation but 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 rationalize empirical findings of a positive or negative green paradox.

As expected, when firms exploit a CPR and are price takers, our results reproduce the findings in the green paradox literature, namely, that firms increase their exploitation of the resource before the policy comes into effect (positive green paradox).[4] 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 a negative green paradox can be supported, where firms reduce their appropriation in anticipation of the future environmental policy. This is a positive result for regulators since the policy not only entails welfare gains at the period when it is implemented,

[1] See Sinn (2008). For a literature review on the green paradox, see Jensen et al. (2015).

[2] Di Maria et al. (2012) finds a 9 percent 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.

[3] Other 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.

[4] For instance, Strand (2007), Hoel (2010), Werf and Di Maria (2011), Smulders et al. (2012), Ploeg (2013), and Di Maria et al. (2012) examine the green paradox in CPRs where firms are price takers.

but potentially in previous periods, as firms approach their exploitation levels to those at the social optimum. Specifically, we show that a negative green paradox is more likely 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.[5] If some of these conditions do not hold, our findings suggest that the introduction of environmental regulation will induce firms to respond by increasing their first-period appropriation under larger parameter values. In this setting, a positive green paradox emerges, which partially offsets the welfare-improving effects of regulation during the second period.

The green paradox literature has warned against the potential effects of environmental policy, as it could aggravate global warming. Our findings, in contrast, suggest that policy makers should not hesitate when regulating polluting industries where some of the above four conditions hold, such as in parts of the mining and fishing sectors, since the announcement of future environmental policies can lead to lower exploitation before their enactment.

Section 2 presents our model. Section 3 then analyzes equilibrium results, as well as its comparative 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 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 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 appropriation by all other $N-1$ firms. Total cost is, therefore, increasing and convex in firm i's appropriation, x_i, and 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 others, 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

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

[5] Marz and Pfeiffer (2015) also identify a reversal of the green paradox but in the context of a monopolist extracting natural resources, and do not study settings with several firms. Similarly, Nachtigall and Rubbelke (2016) find a reversal in the context of resource extraction and rely on firms benefiting from learning-by-doing.

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 θ 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) Emission 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 emission fee $t \geq 0$.

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 emission fees are revenue neutral.

Green paradox. In the next section, we seek to measure the "green paradox"

$$GP \equiv x_i(t^*) - x_i(0).$$

When $GP > 0$, this expression indicates that first-period output increases from $x_i(0)$, when emission fees are absent, to $x_i(t^*)$, evaluated at the second-period fee t^* that the regulator selects in equilibrium. A positive (negative) value for GP indicates that firm i, anticipating a future environmental policy during the second period, increases (decreases) its first-period exploitation.

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

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

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

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

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

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

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 emission fee t, yields

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

which is positive for all parameter values.[6] The optimal fee is increasing in aggregate first-period output, X, and in the number of firms competing for the resource, N; but decreasing in the regeneration rate, β, and in the available stock, θ.[7] 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 emission 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

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

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,

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

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,λ)-pairs, where $\theta = \delta = 1$, $N = 2$ and $\beta = 2/3$. (We consider other

[6] The emission fee t^* first decreases in λ, reaching zero at $\lambda = \frac{b[\theta - X(1-\beta)]}{N-1}$, and then increases in λ; but never becomes negative.

[7] 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.

parameter values below.)

b	λ	$\overline{x}_i$	$x_i^*(t^*)$	$x_i^*(0)$	GP
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 the green paradox.

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.[8] 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 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 green paradox $GP = x_i^*(t^*) - x_i^*(0)$, measuring the increase in appropriation that results from the introduction of environmental policy (if $GP > 0$) or the policy-induced reduction in appropriation (if $GP < 0$).

For illustration purposes, Figure 1 considers those (b, λ)-pairs in Table I, as well as other (b, λ) combinations, and reports the GP next to each point.[9] 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 GP. This is illustrated in the horizontal axis, confirming the finding in the GP literature, namely, that firms increase their first-period appropriation anticipating the loss in future profits they will experience in the second period under regulation.[10] Second, when firms compete a la Cournot ($b > 0$ and $\lambda = 0$), we show a negative GP; as depicted in the points along the vertical axis. Third, the figure reports (b, λ)-pairs with positive GP when the market structure is relatively similar to a standard CPR —low values of b and high values of λ— but a negative GP

[8] 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.

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

[10] 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 $GP = \frac{(N-1)(1-\beta)\delta\theta\lambda(4+3(N-1)\lambda)}{4[1+(N-1)\lambda]^2[2+(N-1)\lambda]^3}$, which is positive since $N \geq 2$ and $\beta \in [0, 1]$ by definition.

when firms do not take prices as given.

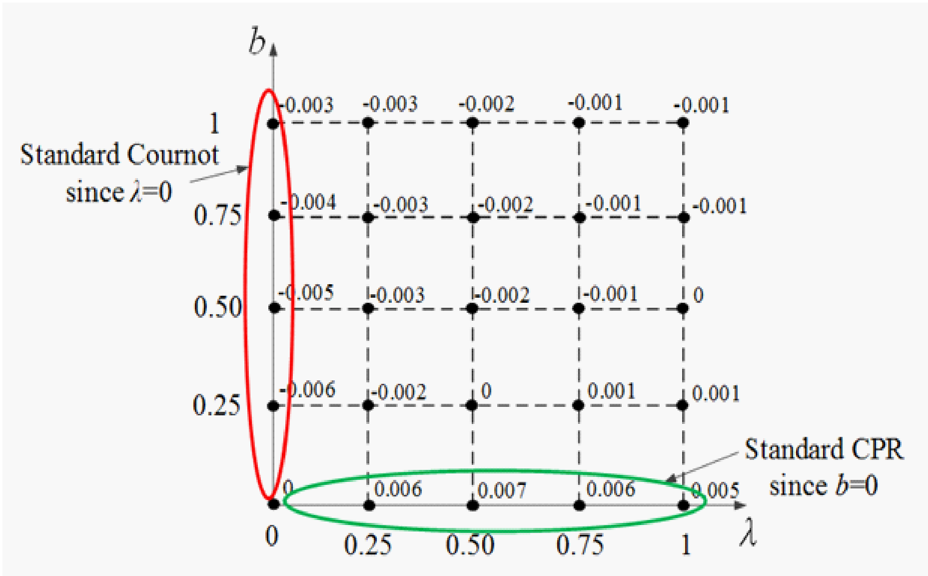

Figure 1. Green paradox under different settings.

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 $b = 0.25$), a more severe externality (higher λ) produces a nil or positive GP. 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 emission fee in the second period, responding with a larger appropriation with than without regulation to partially compensate for their future profit loss.

Comparative statics. Figure 2a illustrates GPs with a scarcer stock, $\theta = 1/2$, keeping all other parameter values unchanged. Relative to Figure 1, Figure 2a shows that GP becomes negative under more restrictive (b, λ)-pairs. Intuitively, a scarcer resource leads to a more stringent fee (since t^* and θ 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 emission fee also becomes more stringent.

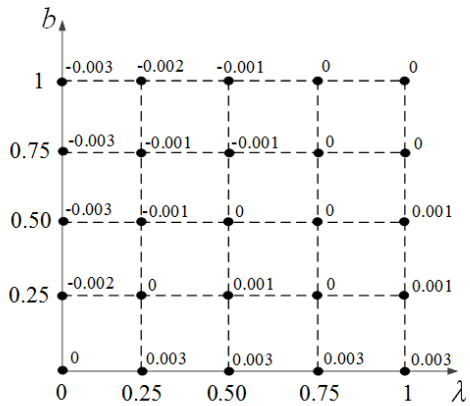

Fig. 2a. GP with θ= 1/2.

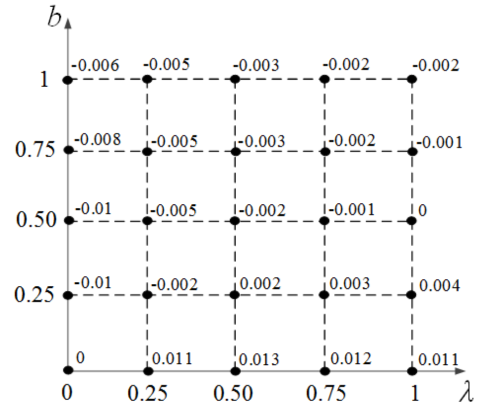

Fig. 2b. GP with $\beta = 1/3$.

Table A3 in the appendix reports GPs using the same parameters as Figure 1, but allowing for $N = 4$ firms. This table shows that GP decreases in absolute value, becoming closer to zero for all (b, λ)-pairs; which occurs both when the GP 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, $GP = 0$ 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 $x_i^*(t^*) = x_i^*(0)$.

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 GP^C, where the C superscript denotes cartel. For comparison purposes, we evaluate these expressions at the same parameter values as Table I,[11] 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 environmental regulation, $x_i^C\left(t^C\right)$, than when they do not, $x_i^C\left(0\right)$, ultimately yielding a larger GP^C. Intuitively, regulation serves as a coordination tool when firms 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 reduction in exploitation is more likely to arise when firms do not act as a cartel than when they do.

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

b	λ	$\overline{x}_i^C$	$x_i^C\left(t^C\right)$	$x_i^C\left(0\right)$	GP^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

Table II. First-period appropriation and the green paradox under cartel.

4 Discussion

Anticipatory effects of taxation. Our above results indicate that firms respond to future regulation by altering their first-period appropriation decisions, that is, emission fees are effective even before they are implemented. In addition, we showed that the GP, understood as how much firms increase their first-period appropriation in anticipation of future emission 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 environmental policy. In particular, if regulators value negative GPs —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 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 emission fees will induce firms to respond increasing their first-period appropriation under larger parameter values, ultimately inducing a positive GP. This partially offsets the welfare-improving effects of regulation during the second period. In contrast, when the above conditions hold, we show that a negative GP is more likely. In words, this entails that the introduction of environmental 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 $GP > 0$ ($GP < 0$, respectively), but essentially 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 emission fees.

[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).

However, when the number of firms competing for the resource is sufficiently large, GP 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 emission 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 emission 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 exploitation of the resource; moving first-period output closer (farther away, respectively) to the social optimum. However, when several firms compete for the resource, our results indicate that the GP approaches zero, indicating that the efficiency gain (loss) that the second-period regulation brings into the first-period vanish.

5 Appendix 1 - Tables

The following tables report the GP for each (b, λ)-pair in Figures 1, 2a, and 2b, respectively. Table A3 shows the GP when $N = 4$ firms.

b	λ	$\bar{x}_i$	$x_i^*(t^*)$	$x_i^*(0)$	GP
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	λ	$\bar{x}_i$	$x_i^*(t^*)$	$x_i^*(0)$	GP
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. GP for $\theta = \delta = 1$, $\beta = 2/3$, and $N = 2$; and Table A2a. GP for $\theta = 1/2$, $\delta = 1$, $\beta = 2/3$, and $N = 2$.

b	λ	$\bar{x}_i$	$x_i^*(t^*)$	$x_i^*(0)$	GP
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	λ	$\bar{x}_i$	$x_i^*(t^*)$	$x_i^*(0)$	GP
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. GP for $\theta = \delta = 1$, $\beta = 1/3$, and $N = 2$; and Table A3. GP for $\theta = \delta = 1$, $\beta = 2/3$, and $N = 4$.

6 Appendix 2 - Appropriation under a cartel

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 $\pi_i^C(t) = \frac{(1-t)^2[\theta-(1-\beta)X]}{4[1+bN[\theta-(1-\beta)X]+(N-1)\lambda]}$. Socially optimal output in this setting coincides with that found in problem (2) in the main body of the paper, Q^{SO}. The optimal emission 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 a fee

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

Evaluating second-period cartel profit $\pi^C(t)$ at fee t^C, we obtain

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

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 (GP) at the same parameter values as Table I. Finally, the upper bound for first-period appropriation in this setting, $\overline{x}_i^C$, is found solving problem (A2) at $\delta = 0$, which yields $\overline{x}_i^C = \frac{\theta}{2[N(1+\lambda+b\theta)-\lambda]}$.

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