Can Poorly Informed Regulators Hinder Competition?*

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Abstract

This paper considers an entry-deterrence game in which environmental policy is set without perfectly observing the incumbent firm's costs. We investigate if regulators, who can have an informational advantage relative to the potential entrant, support entry-deterring practices. The paper demonstrates that, while entry-deterring equilibria only emerge under restrictive conditions when the regulator is perfectly informed, these equilibria arise under larger settings as he becomes uninformed. Furthermore, we show that the regulator is willing to support the incumbent's entry-deterring practices regardless of his degree of information if entry costs are sufficiently high. However, when entry costs are lower, the regulator only sustains this type of practices if he is poorly informed.

Keywords: Entry deterrence; Signaling; Emission fees; Informational advantage.
JEL classification: D82, H23, L12, Q5

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1 Introduction

Environmental regulation is often designed under two constrains: the regulator's imprecise information about firms' costs, and the signaling effect that it can generate on potential entrants, thus affecting entry patterns. The setting of emission fees and quotas under incomplete information contexts has been extensively analyzed by the literature.[1] However, these studies do not consider industries that are subject to entry threats and, hence, overlook the role of regulation as a signal that potential entrants might use in order to assess their market prospects. This paper examines industries whereby the incumbent firm faces entry threats, and seeks to deter entry by concealing its inefficient production costs from potential competitors. In this setting, we investigate if environmental policy affects the incumbent's entry-deterring behavior. In particular, we analyze whether entry deterrence is actually facilitated when the regulator is poorly informed, but hindered when he has access to more accurate information. Our results, hence, highlight the role of the regulator's informational accuracy, since it affects his policy decisions and, consequently, it promotes or limits competition in polluting industries.

Our model considers an entry-deterrence game where firms' production generates an environmental externality that is addressed by emission fees. In this context, the potential entrant is uninformed about the incumbent's costs, either high or low, and observes the regulator's fee and the incumbent's output level, which he uses as two signals before deciding whether to enter the market. The regulator can be as poorly informed as the entrant or, instead, he can benefit from an informational advantage.

We first identify a separating equilibrium in which the low-cost incumbent overproduces in order to signal its type, and thus deters entry; while the high-cost incumbent behaves as under complete information. In this setting, if the regulator was able to observe the incumbent's type, he would anticipate such an overproduction, and thus set an emission fee that induces the socially optimal output. However, when the regulator is only partially informed, he sets an emission fee that minimizes expected inefficiencies. That is, he minimizes the expected deadweight loss that emerges from setting a tax to an incumbent with either high or low costs. Therefore, the regulator faces information inefficiencies, which are measured by the difference between the social welfare that arises in this equilibrium and that under a complete information context. Hence, these inefficiencies are null when the regulator is perfectly informed, but enlarge as he becomes more poorly informed. This result suggests that, when evaluating the welfare properties of environmental policy in industries where potential entrants are uninformed, inefficiencies do not emerge from the entrants' lack of information but, instead, from the regulator's.

We also show the existence of a pooling equilibrium, in which the actions of regulator and incumbent conceal information from the potential entrant, ultimately deterring it from entering. In particular, the regulator chooses the emission fee that corresponds to a low-cost incumbent,

[1] See, for instance, Weitzman (1974), Roberts and Spence (1976), Farrell (1987), Segerson (1988), Xepapadeas (1991), Stavins (1996), and Lewis (1996). In addition, Thomas (1995) empirically analyzes the regulation of industrial wastewater pollution in France when the local regulatory agency has imperfect information.

and both types of firm respond with the same output level, i.e., that of the low-cost incumbent under complete information. In this context, the regulator's policy yields an expected inefficiency. Specifically, when the incumbent's costs are high, setting the fee of the low-cost firm generates a welfare loss, while when the incumbent's type is low such a loss is absent. Nonetheless, deterring entry entails savings in entry costs which, if sufficiently high, offset the former expected inefficiency, thus leading the regulator to support the incumbent's entry-deterring behavior.[2] This support is affected by the regulator's degree of information. In particular, if he is perfectly informed, the pooling equilibrium is sustained only when entry costs are relatively high, given that the inefficiency regulation imposes is certain in this case. However, if the regulator is poorly informed, such inefficiency is less likely to arise, since the incumbent's type could be low. Hence, he is more willing to favor the incumbent's entry-deterring practices under a larger set of entry costs.

From a policy perspective, our findings suggest that, if entry costs are relatively low and governments seek to promote competition, they should stimulate the acquisition of more accurate information by regulatory agencies, such as the environmental protection agency in the U.S. The acquisition of information would hinder the emergence of settings in which regulation unintentionally facilitates entry-deterring behaviors. However, if entry costs are sufficiently high, the regulator is indifferent about the accuracy of his information, since the pooling equilibrium becomes welfare improving regardless of the true type of the incumbent. In this context, the regulator is willing to support the incumbent's entry-deterring practice. Our results, hence, imply that the regulation of industries with large entry costs, such as precious-metals and utilities, does not urgently require the acquisition of accurate information; while industries with low entry costs recommend that the regulator improves his information before designing environmental policy.

Several articles have analyzed firms' entry-deterring practices under contexts in which regulation is absent; see Milgrom and Roberts (1982), Harrington (1986), Bagwell and Ramey (1991), Schultz (1999) and Ridley (2008).[3] However, multiple industries face recurrent regulation since their production generates pollution. In this context, environmental policy can affect firms' behavior, ultimately modifying the conditions under which the equilibrium results identified by the

[2] The entry-deterring role of environmental regulation could explain the lack of entry in the HFCs industry. When the Montreal Protocol sequentially limited the use of CFCs, DuPont was one of the few firms producing substitutes (e.g., HFCs), which helped this firm continue to be a controlling force in the market of refrigerants; as reported in Maxwell and Briscoe (1997). While HFCs were not included in the Montreal Protocol, which regulated ozone depleters, they are regulated by the Kyoto Protocol. In addition, Norway introduced taxes on HFCs since 2003 (and increased them in subsequent years), and other European countries and the U.S. also regulate the use of this refrigerant; see Naess and Smith (2009) and Greenpeace report (2009). DuPont's leading position in this market can be rationalized on their superior technology. However, our results suggest that, even in the absence of cost differentials among firms, the setting of stringent environmental regulation could explain DuPont's market power in this industry.

[3] In addition, Milgrom and Roberts (1986) study an entry-deterrence model in which a firm uses two signals, price and advertising, to convey the quality of its product to consumers. They show that firm's separating effort shrinks because of the presence of an additional signal. We also examine how two different signals (emission fees and output level) convey information to the potential entrant. However, signals originate from two different informed agents in our model: the regulator and the incumbent. Schultz (1999) also analyzes a setting where a potential entrant observes two signals, stemming from two firms competing in a duopoly market which might have different incentives regarding entry.

previous literature can be sustained. Specifically, environmental regulation can alter those settings under which incumbent firms successfully practice entry deterrence. Espinola-Arredondo and Munoz-Garcia (2013) examine whether emission fees can facilitate the emergence of entry-deterring equilibria. Nonetheless, this paper assumes that the regulator is perfectly informed about the incumbent's production costs, given that they have interacted for long periods of time. In contrast, we allow for policymakers to have different degrees of information, since regulators are often only partially informed about industry characteristics, thus helping us to provide a more general analysis of environmental policy.[4] Our results demonstrate that the regulator's lack of precise information can lead him to facilitate the incumbent's entry-deterring practices under a larger set of parameter values. Intuitively, inefficiencies from setting emission fees that can conceal the incumbent's type from the entrant, and thus deter entry, are certain in the model considered in Espinola-Arredondo and Munoz-Garcia (2013), but become only *expected* inefficiencies in the setting that our paper examines.

Our model and results also relate to Espinola-Arredondo et al. (2014), which studies the regulator's decision to set emission fees, and their information content for potential entrants, when such fees cannot be rapidly revised across time if market conditions change. In particular, their model shows that entry deterrence is more likely to arise when environmental regulation cannot be rapidly revised (inflexible regimes) than when regulatory agencies can adjust environmental policy over time (flexible regimes, as that considered in this paper), since the inefficiencies stemming from entry-deterring fees become more permanent under an inflexible than a flexible regime. Our results would, hence, complement those in Espinola-Arredondo et al. (2014), by suggesting that, if countries seek to minimize the possibility that environmental policy can unintentionally limit competition, they should promote well-informed regulatory agencies.

The next section describes the entry-deterrence model with regulation. Section 3 presents the separating equilibrium, where we provide welfare comparisons relative to two benchmarks: complete information settings and entry-deterrence models in which the regulator is absent. Section 4 examines the pooling equilibrium and its welfare properties. Section 5 discusses the policy implications of our results, while section 6 concludes.

2 Model

Let us examine an entry-deterrence game where, in the first period, an incumbent firm operates as a monopolist and, in the second period, it faces the threat of entry of a potential competitor. If entry occurs, incumbent and entrant compete a la Cournot; otherwise, the incumbent maintains its monopoly power. In addition, firms' production generates pollution which is subject to emission fees set by a regulator at the beginning of each period.

[4] Denicolò (2008) examines environmental policy in a context in which an uninformed regulator observes whether a firm acquires a superior technology, in order to signal its cost of regulatory compliance to the government, or an inferior technology. However, two firms are always active in his model, thus neither allowing for firms to practice entry deterrence nor for the regulator to facilitate or hinder these practices. In addition, Denicolò (2008) does not allow for the regulator to sustain different degrees of information.

First period. The incumbent firm faces an inverse demand function $P(q) = 1 - q$ where q denotes first-period output.[5] Hence, the incumbent's profits are

$$\pi_{inc}^{K}(q) = (1-q)\,q - \left(c_{inc}^{K} + t_1\right) q \tag{1}$$

where t_1 represents the first-period emission fee, and the incumbent's marginal costs can be either high or low, i.e., $K = \{H, L\}$, and satisfy $1 > c_{inc}^{H} > c_{inc}^{L} \geq 0$. The regulator's social welfare function is

$$SW(q) = CS(q) + PS(q) + T_1 - ED(q) \tag{2}$$

where $CS(q)$ and $PS(q)$ denote consumer and producer surplus, respectively; $T_1 \equiv t_1 q$ represents tax revenue; and $ED(q)$ is the environmental damage from pollution, $ED(q) \equiv d \times q^2$. (Emission fees are, hence, revenue neutral.)

Second period. In this period, the potential entrant decides whether to join the market, considering that its marginal cost coincides with that of the high-cost incumbent.[6] Hence, profits for incumbent and entrant become

$$\pi_{inc}^{K}(X) = (1-X)\,x_{inc}^{K} - \left(c_{inc}^{K} + t_2\right) x_{inc}^{K} \quad \text{and} \quad \pi_{ent}^{K}(X) = (1-X)\,x_{ent}^{K} - \left(c_{ent}^{H} + t_2\right) x_{ent}^{K} - F \tag{3}$$

where x_{inc}^{K} denotes the K-type incumbent's second-period output, x_{ent}^{K} is the entrant's output when facing a K-type incumbent, $X \equiv x_{inc}^{K} + x_{ent}^{K}$ represents the aggregate output upon entry, and t_2 denotes the second-period emission fee. In addition, the entrant incurs a fixed entry cost $F > 0$, which induces entry when the incumbent's costs are high, but deters it when they are low. In this period, the regulator's social welfare function is analogous to that in the first period, except for being evaluated at aggregate output, X, rather than the monopoly output q.

$$SW(X) = CS(X) + PS(X) + T_2 - ED(X) \tag{4}$$

where $T_2 \equiv t_2\left(x_{inc}^{K} + x_{ent}^{K}\right)$ and $ED(X) \equiv d \times X^2$.

In the next subsection, we describe production and emission fees under a complete information setting in which all agents are informed about the incumbent's production costs; for more details, see Espinola-Arredondo and Munoz-Garcia (2013); while the following subsection discusses the incomplete information context.

[5] Using this inverse demand function provides relatively compact equilibrium results, facilitates their interpretation, and their comparison across complete and incomplete information settings. Nonetheless, for generality Appendix 1 extends our model to an inverse demand function $p(q) = a - bq$, showing that our qualitative results are essentially unaffected.

[6] This assumption can be rationalized by the fact that entrants lack experience in the industry; or alternatively, they still ignore some of the administrative details of complying with the environmental regulation.

2.1 Complete information

First period. In a complete information environment, the incumbent monopolist produces according to an output function that maximizes (1), i.e., $q^K(t_1) = \frac{1-\left(c^K_{inc}+t_1\right)}{2}$. In addition, the regulator finds the socially optimal output q^K_{SO} that maximizes (2), i.e., $q^K_{SO} \equiv \frac{1-c^K_{inc}}{1+2d}$. In order to induce such an output level, he needs to set an emission fee $t^K_1 = (2d-1)\frac{1-c^K_{inc}}{1+2d}$, i.e., t^K_1 solves $q^K(t_1) = q^K_{SO}$. Therefore, emission fees are only positive for sufficiently high environmental damages, $d > 1/2$.[7]

Second period, No entry. During the second period, entry does not occur when the incumbent's costs are low. As a consequence, if entry does not ensue (NE), the monopolist produces according to the same output function as in the previous period, thus leading the regulator to maintain fees at $t^{L,NE}_2 = t^L_1$.

Second period, Entry. In contrast, if the incumbent's costs are high and thus entry occurs (E), firms respond producing the output levels that maximize (3), i.e., $x^{H,E}_i(t_2) = \frac{1-2c^H_i+c^H_j-t_2}{3}$ where $i = \{inc, ent\}$ and $j \neq i$. The regulator must, hence, determine the socially optimal aggregate output in this context, X^H_{SO}, that maximizes (4). In particular, given the symmetry in the first- and second-period social welfare function, it is straightforward to show that the socially optimal aggregate output level in the second period, X^H_{SO}, coincides with that in the first period, q^H_{SO}. However, the regulator needs to use different fees in the second period in order to induce output X^H_{SO} depending on whether entry ensues or not. The second-period fee, $t^{H,E}_2$, is obtained by solving $x^{H,E}_i(t_2) + x^{H,E}_i(t_2) = \frac{1-c^H_{inc}}{1+2d}$, i.e., $t^{H,E}_2 = (4d-1)\frac{1-c^H_{inc}}{2(1+2d)}$.[8] As in standard models of environmental taxation, see Buchanan (1969), the emission fee that the regulator imposes to the duopoly is more stringent than that under monopoly, i.e., $t^{H,E}_2 > t^{H,NE}_2$, since aggregate output under the unregulated duopoly is larger than monopoly output, and thus more distant to the social optimum.

2.2 Incomplete information

We now analyze the case in which the regulator and the potential entrant are uninformed about the incumbent's costs. In particular, we consider the following entry-deterrence game:

1. In the first stage, the incumbent privately observes its marginal cost, either high, c^H_{inc}, or low, c^L_{inc}.

   (a) The regulator, unable to observe this information, sets an emission fee t_1 to the single incumbent operating in the industry, and this firm responds producing an output level

[7] Intuitively, if $d \leq 1/2$, the market failure from the insufficient production under monopoly is more significant than that from pollution, ultimately leading the regulator to set a subsidy, rather than a tax, in order to induce an increase in output levels.

[8] In the equilibrium of the complete information game, entry only occurs if the incumbent's costs are high, and thus the regulator sets a duopoly fee $t^{H,E}_2$ in the second period upon entry. However, if the incumbent's costs are low and, by mistake, the potential entrant joins the industry (off-the-equilibrium path), the regulator still needs to set a duopoly fee $t^{L,E}_2$. As shown in Espinola-Arredondo and Munoz-Garcia (2013), such a fee is $t^{L,E}_2 = \frac{(1+2d)(1-c^H_{inc})-(2-2d)(1-c^L_{inc})}{2(1+2d)}$. Importantly, both of these fees are positive as long as firms' costs are not extremelly asymmetric, i.e., $c^L_{inc} < c^H_{inc} < \frac{1+2dc^L_{inc}}{1+2d} \equiv \alpha$, a condition we consider throughout the paper.

$q(t_1)$.

(b) A potential entrant, also uninformed about the incumbent's costs, observes both the emission fee t_1 and the output level $q(t_1)$, and updates its priors about the incumbent's type being high, $p \in (0,1)$, to the posterior belief $\mu\left(c_{inc}^{H}|t_1, q(t_1)\right)$ given the pair of signals $(t_1, q(t_1))$.

2. In the second period, the entrant decides whether to join the market.

(a) If entry does not occur (NE), the incumbent maintains its monopoly power, and produces $x_{inc}^{K,NE}$ for all $K = \{H, L\}$.

(b) If entry ensues (E), firms compete a la Cournot, simultaneously choosing output levels $x_{inc}^{K,E}$ and $x_{ent}^{K,E}$, for the incumbent and entrant, respectively.

(c) In addition, the regulator designs the second-period emission fee t_2 in order to induce the socially optimal output, both when entry occurs and when it does not.

In order to facilitate the comparison of our results, we consider that players become informed about the incumbent's costs in the second stage. This assumption, common in the literature on entry-deterrence games where regulation is absent, helps us determine how the presence of the regulator facilitates or hinders the incumbent's entry-deterring practices. (For completeness, in the Discussion section we examine how our results are affected if, instead, the regulator is still uninformed during the second stage of the game.)

The regulator, despite being uninformed, receives a costless report which can allow him to more accurately determine the incumbent's type. The entrant, however, does not have access to such information. We consider that the governmental agency elaborating these reports is separated from the regulatory body receiving them and setting emission fees. Hence, the regulator cannot choose whether to receive the reports, nor can he affect their accuracy. For instance, these reports could include those elaborated every period by agencies such as the Environmental Protection Agency or the Federal Trade Commission in the U.S. (but not released to the public), and thus prepared before the government decides the first-period emission fee.

While both regulator and entrant assign a probability p to the incumbent's costs being high, the information provided by the report modifies the regulator's prior to p^{β}, where parameter $\beta \in [0, +\infty)$ represents how well informed about the incumbent's type he is. In particular, if the regulator initially believes that the incumbent's costs are high, $p > 1/2$, the information provided by the report, as captured in β, can help him emphasize his initial prior, if $p^{\beta} > p > 1/2$; moderate it, if $p > p^{\beta} \geq 1/2$; or instead make him believe that the incumbent's costs are likely to be low, $p > 1/2 > p^{\beta}$. As depicted in Figure 1a and 1b, when the initial priors are $p = 0.8$, the first case arises if $\beta \in [0, 1]$ where, after the report, the regulator assigns a larger probability weight on the incumbent's costs being high than the entrant does, $p^{\beta} > p$. The second case emerges when p^{β} lies below the 45^{0}-line but still above $1/2$, thus moderating the regulator's initial belief. Specifically, this occurs when $\beta \in \left(1, \frac{\ln 1/2}{\ln p}\right]$, where $\beta = \frac{\ln 1/2}{\ln p}$ solves $p^{\beta} = 1/2$. Finally, the third case arises when p^β lies below $1/2$, which implies a larger value of β, i.e., $\beta \in \left(\frac{\ln 1/2}{\ln p}, +\infty\right)$. A similar argument applies when the regulator's priors lead him to believe that the incumbent's costs are low, $p < 1/2$. In the extreme case, if $\beta = 0$, the regulator is certain about facing a high-cost incumbent, i.e., $p^\beta = 1$; if $\beta = 1$, he is as poorly uninformed about the incumbent's type as the potential entrant, thus making the report useless; and if $\beta \to +\infty$, he is sure about facing a low-cost incumbent, i.e., $p^\beta = 0$.[9]

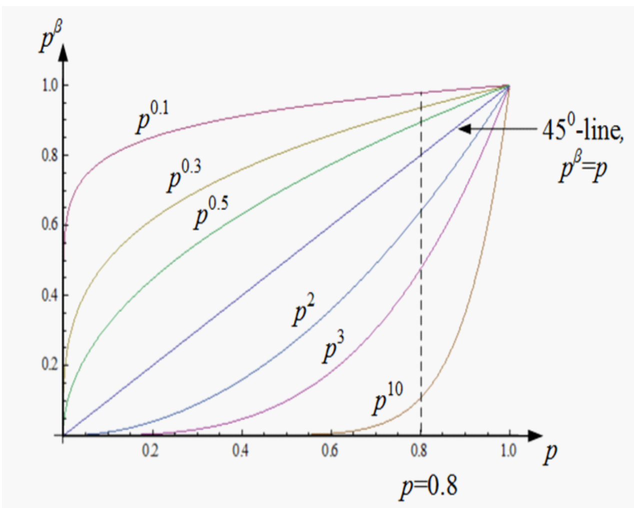

Fig 1a. Entrant's, p, and Regulator's, p^β, priors.

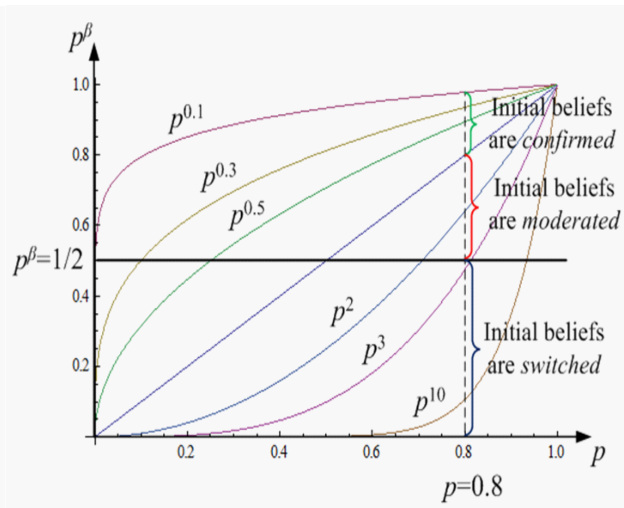

Fig 1b. Effect of β on the regulator's priors.

Figure 1a also allows for a representation of the regulator's informational advantage using the area between p^β and p, normalized over $1/2$, which is the largest possible area between these two functions. In particular, let $RIC \equiv \frac{\int_0^1 (p^\beta - p)dp}{1/2}$ denote the regulator's information coefficient, which reaches its upper (lower) bound, $RIC = 1$ ($RIC = -1$) when the regulator is certain about the incumbent's costs being high (low, respectively), and lies in its midpoint, $RIC = 0$, when the regulator is as uninformed as the entrant.[10]

Unlike Espinola-Arredondo and Munoz-Garcia (2013), which considers that the regulator perfectly observes the incumbent's costs, our model examines a setting in which he can be fully or partially informed (when $RIC \neq 0$), or totally uninformed ($RIC = 0$), thus allowing for different signaling patterns, as the next section demonstrates.

In addition, since the regulator becomes informed about the incumbent's costs in the second-period game, he can set emission fees to induce the same socially optimal output, X_{SO}^K, both when entry ensues and when it does not. As a consequence, second-period welfare also coincides with

[9] Note that in the extreme cases in which $p = 0$ or $p = 1$, both the regulator and the entrant are fully informed about the incumbent's type, and thus their priors coincide, making the value of parameter β inconsequential.

[10] Note that $RIC \equiv \frac{\int_0^1 (p^\beta - p)dp}{1/2} = \frac{2}{1+\beta} - 1$, which originates at 1 when $\beta = 0$, and decreases in β, ultimately reaching -1 when $\beta \to +\infty$.

and without entry, except for entry costs F. Therefore, we hereafter focus on first-period emission fees and output.

3 Separating equilibrium

We next show that there exists a separating Perfect Bayesian Equilibrium (PBE) in which the incumbent selects a type-dependent output function. If the regulator was perfectly informed about the incumbent's type, he could design emission fees to induce a socially optimal output level $q_{SO}^{K} \equiv \frac{1-c_{inc}^{K}}{1+2d}$. However, the regulator's lack of accurate information leads him to set an emission fee that entails inefficiencies. Specifically, he must set a first-period fee that minimizes the expected deadweight loss that arises from setting inefficient taxes to either type of incumbent (i.e., a second-best environmental policy). In particular, the regulator's problem is

$$\min_{t_1 \geq 0} \; p^{\beta} \left|DWL_H(t_1)\right| + \left(1-p^{\beta}\right) \left|DWL_L(t_1)\right| \tag{5}$$

where, on one hand, $DWL_H(t_1) \equiv \int_{q^H(t_1)}^{q_{SO}^H} \left[MB^H(q) - MD(q)\right] dq$ denotes the deadweight loss from setting a fee t_1 to the high-cost incumbent, and $q^H(t_1) = \frac{1-c_{inc}^H - t_1}{2}$ represents the output function that maximizes the incumbent's first-period profits. Furthermore, $MB^H(q)$ and $MD(q)$ are the social marginal benefit (damage, respectively) from increasing output for this incumbent.[11] On the other hand, $DWL_L(t_1) \equiv \int_{q_{SO}^L}^{q^A(t_1)} \left[MB^L(q) - MD(q)\right] dq$ represents the efficiency loss from imposing a fee t_1 to the low-cost incumbent, and $q^A(t_1)$ denotes the output function that this firm selects in order to signal its low costs to potential entrants, thus deterring entry, i.e., $q^A(t_1)$ exceeds the output function under complete information $q^L(t_1)$, as shown in the next Proposition. (For presentation purposes, Proposition 1 does not describe the entrant's beliefs upon observing signal pairs $(t_1, q(t_1))$, but we discuss them in detail at the end of this subsection.)

Proposition 1. *A separating PBE can be supported when priors satisfy* $p > \frac{F-D_{ent}^L}{D_{ent}^H - D_{ent}^L} \equiv \overline{p} > \mu'$, *in which the regulator selects an emission fee,*

$$t_1^* \equiv \frac{2d-1+\gamma(1-p^{\beta}) + \left[p^{\beta}(2+\gamma) - \rho - \gamma\right] c_{inc}^H + 2(1-p^{\beta})c_{inc}^L}{\rho}$$

which solves problem (5), $\gamma \equiv \sqrt{3\delta}$, $\rho \equiv 1+2d$, $\mu' \equiv \mu\left(c_{inc}^H | q^A(t_1^*), t_1^*\right)$, *and* δ *denotes the discount factor. The incumbent responds choosing output function* $q^H(t_1)$ *when its costs are high and* $q^A(t_1) = \frac{(1-c_{inc}^H)\rho - \gamma}{2} - \frac{\rho}{2}t_1$ *when its costs are low, where* $q^A(t_1) > q^L(t_1)$, *if and only if the entrant's costs are sufficiently low, i.e.,* $c_{ent} < \alpha_1 \equiv \frac{\gamma + \rho c_{inc}^L}{\gamma + \rho}$, *where* $\alpha_1 < \alpha$.

Hence, the low-cost incumbent only exerts a separating effort, $q^A(t_1)$, when its competition in

[11] For more details about the calculation of this deadweight loss, see the proof of Proposition 1.

the post-entry game is tough, i.e., the entrant's costs are relatively low.[12] In contrast, the high-cost incumbent does not find it profitable to mimic the output decision of the low-cost firm, and behaves as under complete information, choosing $q^H(t_1)$. Anticipating these production decisions from each type of incumbent, the regulator sets an emission fee that minimizes the expected inefficiencies that tax t_1^* entails. The following corollary examines how this emission fee is affected when the regulator has access to different degrees of information.

Corollary 1. *Emission fee t_1^* is increasing in β, implying that the regulator imposes more stringent emission fees as he becomes more certain that the incumbent's costs are low, if and only if $c_{inc}^H < \min\left\{\alpha, \frac{2+\gamma-2(1-c_{inc}^L)}{2+\gamma}\right\}$. In addition, when $RIC = 1$, this fee becomes $t_1^H \equiv \frac{(2d-1)(1-c_{inc}^H)}{\rho}$; when $RIC = -1$, it is $t_1^A \equiv \frac{(1-c_{inc}^H)(\rho+\gamma)-2(1-c_{inc}^L)}{\rho}$; and when $RIC = 0$, the fee is*

$$t_1^U \equiv \frac{2d - 1 + [p(2+\gamma) - \rho - \gamma]\, c_{inc}^H + \left(2c_{inc}^L + \gamma\right)(1-p)c_{inc}^L}{\rho}.$$

Therefore, when the regulator is certain about facing a high-cost incumbent, $RIC = 1$, he anticipates that it produces with output function $q^H(t_1)$, and sets an emission fee that coincides with that under complete information, t_1^H, thus inducing a socially optimal output q_{SO}^H. In contrast, when he is sure about facing a low-cost firm, $RIC = -1$, he predicts that the incumbent uses an output function $q^A(t_1)$, which exceeds that under complete information $q^L(t_1)$, signaling its type and deterring entry. As a consequence, in order to still induce the socially optimal output q_{SO}^L achieved under complete information, the regulator must set a more stringent emission fee, i.e., t_1^A solves $q^A(t_1) = q_{SO}^L$.[13] However, when the regulator is only partially informed, i.e., $RIC \in (-1, 1)$, emission fee t_1^* can be expressed as a weighted average of the optimal emission fee the regulator would set when being perfectly informed that the incumbent's costs are high, t_1^H, and that when they are low, t_1^A, i.e., $t_1^* = p^\beta t_1^H + \left(1 - p^\beta\right) t_1^A$.[14] Figure 2 depicts emission fee t_1^*, illustrating its increasing pattern as the regulator becomes more certain that the incumbent's costs are low, i.e., from t_1^H when $\beta = 0$ to t_1^U when $\beta = 1$ and t_1^A when $\beta \to +\infty$.[15] In addition, emission fee t_1^* becomes more stringent as the probability that the incumbent's costs are high, p, decreases; as depicted in the upward shift of t_1^* in the figure. In this context, the regulator is more certain about the incumbent's costs being low, and sets a higher tax in order to ameliorate the excessive pollution

[12] In addition, output decision $q^A(t_1)$ implies the smallest deviation from the low-cost incumbent's action under a complete information setting, i.e., it is the least-costly separating equilibrium that survives the Cho and Kreps' (1987) Intuitive Criterion, as shown in the proof of Proposition 1.

[13] These two results, whereby the regulator perfectly observes the incumbent's type, hence embody those in Espinola-Arredondo and Munoz-Garcia (2013) as special cases.

[14] Unlike standard signaling games in which the agent sending a particular message is perfectly informed, the regulator, when being as uninformed about the incumbent's costs as the potential entrant, is unable to condition emission fees on the incumbent's type.

[15] The figure assumes no discounting, production costs $c_{inc}^H = 9/20$ and $c_{inc}^L = 1/4$, and environmental damage $d = 3/4$. Other parameter combinations yield similar results, and can be provided by the authors upon request.

this firm generates.

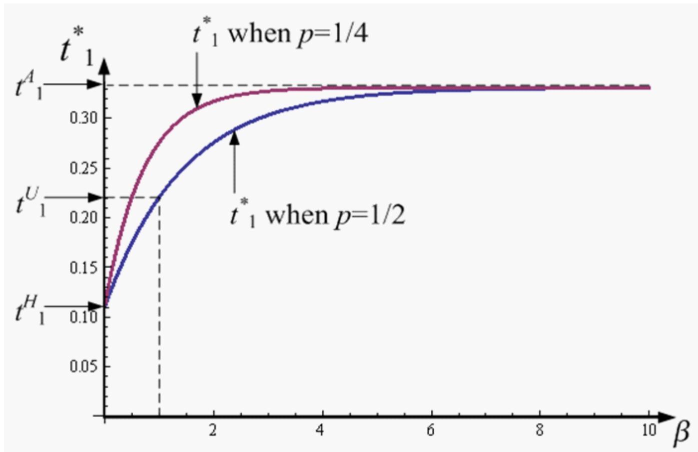

Fig 2. Emission fee t_1^* and β.

Beliefs: The separating equilibrium can be sustained as long as the potential entrant observes "consistent" signals from the regulator and the incumbent. The entrant's beliefs can be examined considering three different cases: (1) $t_1^* < t_1^U$; (2) $t_1^* > t_1^U$; and (3) $t_1^* = t_1^U$. In the first case, after observing an emission fee t_1^* that is less stringent than t_1^U, this firm suspects that the regulator must have relatively accurate information about the incumbent's costs being high, i.e., $RIC > 0$. If the incumbent's type is indeed high, this firm selects equilibrium output level $q^H(t_1^*)$, which confirms the entrant's suspicion, thus attracting entry. If, instead, the regulator's information was inaccurate, and the incumbent's type is in fact low, the separating equilibrium prescribes that this firm chooses $q^A(t_1^*)$. In this setting, the entrant observes two contradictory signals, but does not know whether the regulator's information was incorrect, or if the high-cost incumbent is mimicking the output decision of the low-cost firm in order to deter entry. Hence, the entrant cannot assign full probability to any type of incumbent, and holds beliefs $\mu\left(c_{inc}^H | q^A(t_1^*), t_1^*\right) \equiv \mu' \in [0,1]$. Finally, if equilibrium fee t_1^* is followed by an off-the-equilibrium output level $q(t_1^*) \neq q^H(t_1^*), q^A(t_1^*)$, the entrant observes inconsistent signals and enters.

In the second case, emission fee t_1^* is more stringent than t_1^U, making the entrant suspect that the incumbent's costs are low, i.e., $RIC < 0$. In this context, if the incumbent's type is indeed low, it responds producing output level $q^A(t_1^*)$, thus confirming the entrant's suspicion, who stays out of the market. If the regulator's information is inaccurate, and the incumbent's type is actually high, the entrant observes $t_1^* > t_1^U$ followed by $q^H(t_1^*)$. While the two signals seem contradictory, the potential entrant knows that a low-cost incumbent would never deviate from $q^A(t_1^*)$ to $q^H(t_1^*)$, since doing so would attract entry. Hence, the entrant relies on the incumbent's output decision alone, and enters. Similarly as in case (1), equilibrium fees responded by off-the-equilibrium output levels induce entry.[16] Finally, in case (3) the entrant observes an emission fee $t_1^* = t_1^U$, which allows this firm to infer that the regulator is as poorly informed as it is, i.e., $RIC = 0$, implying that the entrant only relies on the incumbent's output level, either $q^H(t_1^*)$ or $q^A(t_1^*)$, in order to identify the incumbent's type.

3.1 Welfare properties of the separating equilibrium

In this subsection we evaluate the welfare that arises under the separating equilibrium, $W_{SE}^{K,R}$, allowing for different degrees of information, RIC. We also compare it against the welfare that emerges in a context in which the regulator is absent, $W_{SE}^{K,NR}$, and a setting in which both the regulator and the potential entrant are perfectly informed about the incumbent's costs, $W_{CI}^{K,R}$.

Corollary 2. *When the regulator is present, social welfare in the separating equilibrium is strictly lower than under complete information for all $RIC \neq 0$, i.e., $W_{SE}^{K,R} < W_{CI}^{K,R}$, both when the incumbent's costs are high and low; but it coincides when $RIC = -1$ and $RIC = 1$, i.e., $W_{SE}^{K,R} = W_{CI}^{K,R}$. In addition, social welfare in a separating equilibrium in which the regulator is present is weakly larger than in one where he is absent, i.e., $W_{SE}^{K,R} \geq W_{SE}^{K,NR}$.*

In the separating equilibrium, if the incumbent's costs are high, the incumbent produces according to $q^H(t_1)$. However, the uninformed regulator cannot condition the first-period emission fee on the incumbent's type, thus generating inefficiencies, i.e., $W_{SE}^{H,R} \leq W_{CI}^{H,R}$. Under complete information, in contrast, these inefficiencies do not exist, since he can set emission fees according to the incumbent's costs. Hence, inefficiencies that emerge from the regulator's inaccurate information are maximal when he is as uninformed as the potential entrant, $RIC = 0$, but approach zero when he becomes better informed about the incumbent's high costs, i.e., $RIC = 1$. Figure 3a compares $W_{SE}^{H,R}$ and $W_{CI}^{H,R}$ for $\beta \in [0, 1]$, where the shaded area represents the information inefficiencies.

Similar inefficiencies arise when the incumbent's costs are low. In particular, under complete information, the regulator induces a socially optimal output level during both periods. Under incomplete information, the regulator anticipates that the low-cost firm increases output (and, as a consequence, pollution) to signal its type and deter entry. However, he cannot set an efficient emission fee given his inaccurate information, thus entailing inefficiencies, i.e., $W_{SE}^{L,R} \leq W_{CI}^{L,R}$, as depicted in figure 3b. These inefficiencies nonetheless disappear when the regulator is perfectly informed about the incumbent's low type, i.e., $W_{SE}^{L,R} = W_{CI}^{L,R}$.

[16] A similar result applies if one follows the notion of "unprejudiced beliefs" by Schultz (1999), whereby the entrant's beliefs would be compatible with the strategy of the non-deviating player, the regulator. Thus, the entrant would assign full probability to the incumbent's costs being low, deterring it from the industry. While these beliefs would eliminate the low-cost incumbent's need to separate from its complete-information strategy in order to prevent entry, it would not affect the high-cost firm's strategy. Furthermore, note that when both regulator and incumbent select pooling strategies, as the following section analyzes, the use of unprejudiced beliefs (or the consistent beliefs discussed above) do not restrict the entrant's beliefs. In such a setting, we apply Cho and Kreps' (1983) Intuitive Criterion to limit the set of pooling equilibria with sensible beliefs.

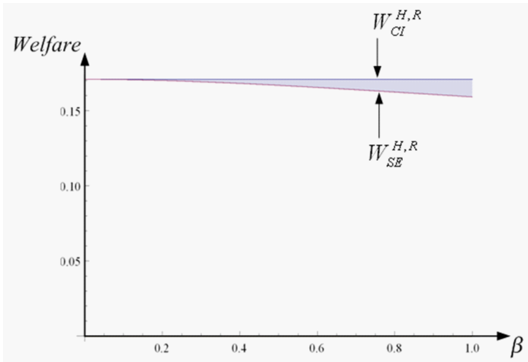

Fig 3a. High-cost incumbent.

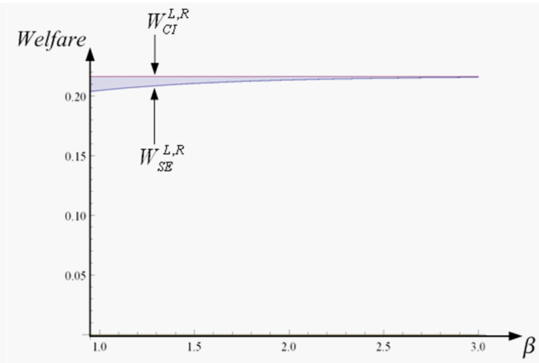

Fig 3b. Low-cost incumbent.

Hence, emission fees from an uninformed regulator might generate large inefficiencies; thus suggesting that regulation in these contexts becomes less beneficial. Nonetheless, this finding does not imply that the regulator's task is unnecessary. Instead, even if the regulator is poorly informed, environmental regulation reduces the excessive amount of pollution in the first-period game, which arises from the incumbent's overproduction. In particular, when he is absent, first-period production is $q^A(0)$, whereas his presence reduces it to $q^A(t_1^*)$, where $q^A(0) > q^A(t_1^*) > q^A(t_1^A) = q_{SO}^L$, thus approaching it to the social optimum. Therefore, the introduction of emission fees entails a welfare improvement, which becomes larger as the regulator is more accurately informed about the incumbent's costs.

4 Pooling equilibrium

In this section, we examine the pooling equilibrium in which the actions of regulator and incumbent conceal information about the incumbent's costs from the potential entrant and, given its low priors, entry is successfully deterred. In particular, we investigate whether a less informed regulator can facilitate the emergence of the incumbent's entry-deterring practices under larger parameter conditions.

Proposition 2. *A pooling PBE can be supported when priors satisfy $p \leq \overline{p}$, in which the regulator sets a type-independent fee t_1^L, both types of incumbent produce according to output function $q^L(t_1)$, and entry is deterred, if entry costs are sufficiently high, i.e., $F > \overline{F}(\beta)$, where*

$$\overline{F}(\beta) \equiv \frac{\sqrt{\delta}\lambda\left(4\sqrt{3}\omega - 3\sqrt{\delta}\lambda\right) + \left(2p^{\beta} - p^{2\beta}\right)\left(\gamma^2\lambda^2 - 4\gamma\lambda\omega + 4\omega^2\right)}{8\delta\rho}$$

and $\lambda \equiv \left(1 - c_{inc}^H\right)$, and $\omega \equiv \left(c_{inc}^H - c_{inc}^L\right)$. In addition, for admissible entry costs $D_{ent}^H > F > D_{ent}^L$, *condition $F > \overline{F}(\beta)$ implies that the high-cost incumbent's costs satisfy $c^H_{inc} < \alpha_2$, where*

$$\alpha_2 \equiv \frac{2\left(1-c^L_{inc}\right)\left[\rho\left(3+\eta+6d\tau\right)\delta\right]^{1/2}+4\rho\eta c^L_{inc}+2\gamma\rho\tau(1+c^L_{inc})}{4\gamma\rho+\left(5+6d\right)\delta-\rho p^{\beta}\left(4+4\gamma+3\delta\right)\left(2-p^{\beta}\right)}$$

and $\eta \equiv p^{\beta}\left(p^{\beta}-2\right)$, $\tau \equiv \left(p^{\beta}-1\right)^2$, $\alpha_2 < \alpha_1$, and D^K_{ent} denotes the entrant's duopoly profit when facing a type-K incumbent.

Hence, for the pooling equilibrium to arise, the high-cost incumbent must be sufficiently symmetric to the low-cost firm, $c^H_{inc} < \alpha_2$, since otherwise its mimicking effort would be too costly. In this case, the uninformed regulator faces two options: on one hand, he can set an emission fee t^*_1 that, while not being socially optimal, minimizes expected information inefficiencies; as described in the previous section. This fee would satisfy $t^*_1 \leq t^U_1$, thus allowing the entrant to suspect that the incumbent's costs might be high, which ultimately induces the incumbent to produce $q^H(t^*_1)$, thus attracting entry. On the other hand, the regulator could instead choose an emission fee t^L_1 that, despite generating larger inefficiencies than fee t^*_1, supports the high-cost incumbent's concealing strategy. In particular, a tax t^L_1 followed by an output level $q^L(t^L_1)$ leads the entrant to stay out given its low priors, $p \leq \overline{p}$. Therefore, the regulator compares the benefit from deterring entry, captured by the savings in entry costs F, against the inefficiencies that emerge from setting fee t^L_1, and, hence, supports the incumbent's entry-deterring practices when entry costs are relatively large, i.e., $F > \overline{F}(\beta)$. Figure 4 illustrates the region of admissible entry costs $D^H_{ent} > F > D^L_{ent}$, and the area above cutoff $\overline{F}(\beta)$ for which entry deterrence can be sustained.[17]

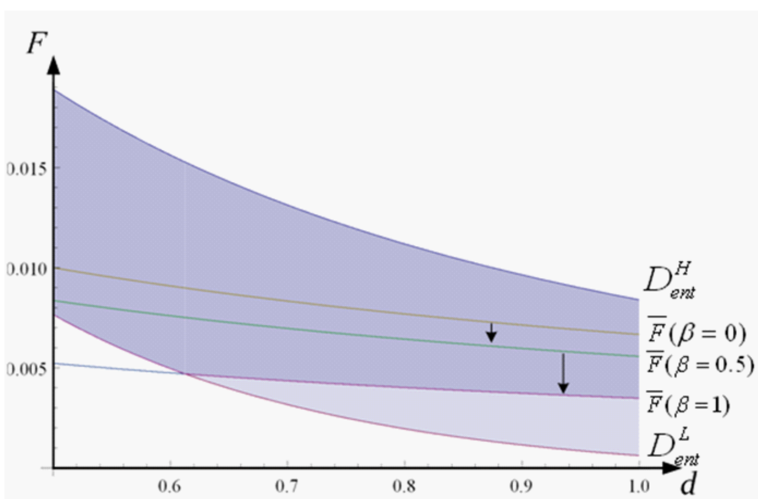

Fig 4. Entry costs sustaining the Pooling PBE.

[17]For consistency, the figure also considers parameter values $c^H_{inc} = 9/20$, $c^L_{inc} = 1/4$ and $p = 1/2$. These are admissible parameter conditions in the pooling equilibrium. In particular, cutoff α_2 increases in β but decreases in d, thus reaching its minimum, 0.46, at $\beta = 0$ and $d = 1$, which still satisfies $c^H_{inc} = 9/20 < \alpha_2$.

In addition, the figure depicts $\overline{F}(\beta)$ evaluated at different values of β. In particular, when the regulator is perfectly informed about the incumbent's costs being high, $\beta = 0$, he anticipates that setting fee t_1^L would generate a certain inefficiency. Hence, the regulator is only willing to support the incumbent's entry-deterring practices if entry costs are relatively high; as depicted in the dark shaded region above cutoff $\overline{F}(0)$. However, when he becomes less informed, and assigns a larger probability weight to the incumbent's cost being low, setting fee t_1^L only entails an expected inefficiency. Since this expected inefficiency is lower than the certain welfare loss that emerges when $\beta = 0$, the regulator is, hence, willing to behave as prescribed in the pooling equilibrium under larger entry costs, i.e., cutoff $\overline{F}(\beta)$ decreases in β as depicted in figure 4. In other words, as the regulator becomes more poorly informed, he supports the incumbent's entry-deterrence practices under larger conditions.

Furthermore, note that as the environmental damage becomes more severe (higher values of d) the regulator supports the incumbent's entry-deterring practices under a larger set of parameter conditions. Intuitively, when pollution is very damaging (e.g., $d = 0.9$ in figure 4), the inefficiency that arises from overtaxing the high-cost incumbent in the pooling equilibrium diminishes. As a consequence, the region of entry costs for which the regulator facilitates entry deterrence expands, i.e., the area above cutoff $\overline{F}(\beta)$ enlarges.

Finally, our results are sensitive to cost symmetries. In particular, cutoff $\overline{F}(\beta)$ decreases as firms become more symmetric. Intuitively, the regulator experiences a smaller welfare loss from setting an inefficient fee t_1^L to a (potentially) high-cost incumbent, thus implying that he is more willing to support the incumbent's entry-deterring practices under larger conditions, i.e., for a larger region of entry costs.

4.1 Welfare properties of the pooling equilibrium

We next compare the welfare that arises in the regulated pooling equilibrium, $W_{PE}^{K,R}$, with that when the regulator is absent, $W_{PE}^{K,NR}$. For completeness, we also develop comparisons with the social welfare under complete information, $W_{CI}^{K,R}$.

Corollary 3. *When the regulator is present, social welfare in the pooling equilibrium is strictly higher than under complete information, $W_{PE}^{K,R} > W_{CI}^{K,R}$, if and only if $F > \overline{F}(0) \equiv \frac{\omega^2}{2\delta\rho}$. In addition, social welfare in a pooling equilibrium in which the regulator is present is weakly larger than in one where he is absent, i.e., $W_{PE}^{K,R} \geq W_{PE}^{K,NR}$, under all parameter values.*

This corollary implies that, in the case that the regulator is perfectly informed about the incumbent's costs being high, $\beta = 0$, social welfare in the pooling equilibrium of the entry-deterring game is larger than under a complete information setting (where all agents are informed) for all admissible entry costs in which this equilibrium exists. However, when the regulator becomes uninformed, $\beta > 0$, this welfare ranking does not necessarily hold. In particular, the pooling equilibrium can now be sustained for lower entry costs (as depicted in figure 4), but equilibrium welfare is only larger than under complete information if entry costs are sufficiently high, $F > \overline{F}(0)$.

In particular, the regulator supports the incumbent's entry-deterring behavior when the inefficiency that fee t_1^L generates relative to its alternative, t_1^*, is offset by the savings in entry costs. However, when evaluating the inefficiency that emerges in this equilibrium relative to a complete information context, whereby the regulator sets t_1^H, the inefficiency from fee t_1^L becomes larger, thus offsetting the savings in entry costs for all $F < \overline{F}(0)$. Finally, note that the presence of the regulator is welfare improving, since he ameliorates the excessive pollution that the high-cost incumbent produces when mimicking the output decision of the low-cost firm.

5 Discussion

The uninformed entrant is not the problem. The regulator's imprecise information about the incumbent's costs can give rise to information inefficiencies (figure 3). Specifically, if the regulator is certain about the incumbent's type, while the potential entrant is still uninformed, this inefficiency approaches zero. In contrast, it enlarges when the regulator is as poorly informed as the potential entrant. From a policy perspective, one may think that the excessive production (and pollution) that arises in the separating equilibrium can be avoided by disseminating information about the low-cost incumbent to the potential entrant, hence resulting in a complete information setting. However, our findings suggest that the presence of an uninformed entrant is not the root of the problem, but the poorly informed regulator is. In particular, when the regulator becomes better informed, he can address the inefficiencies arising from overproduction, thus making social welfare in the signaling game similar to that under a complete information setting.

Lobbyists' incentives to promote stringent regulation. While an informed regulator only supports the incumbent's entry-deterring practices when entry costs are relatively high, a poorly informed regulator becomes more willing to favor these practices under a larger set of entry costs. Hence, if governments seek to promote competition, they should support the acquisition of accurate information by environmental regulatory agencies, since that would reduce the contexts in which entry deterrence emerges. Otherwise, industry lobbyists would have incentives to influence regulatory agencies in order to promote emission fees such as t_1^L which, despite being stringent, can ultimately help them to prevent entry; as shown in a complete information setting by Schoonbeek and de Vries (2009).

The regulator does not necessarily prefer to be informed. In the pooling PBE the regulator sets a fee t_1^L and the incumbent responds with output $q^L(t_1^L)$, entailing a welfare level which is independent on the regulator's degree of information, β. This result, however, does not imply that the regulator is indifferent between being perfectly informed or uninformed about the incumbent's costs. In particular, if entry costs are intermediate, the regulator would set a fee t_1^L when being as poorly informed as the potential entrant, but he would not when he becomes perfectly informed. Hence, for this range of entry costs, the regulator still prefers to be as well informed as possible when designing environmental policy. In contrast, if entry costs are extremely high, i.e., $F > \overline{F}(0)$, the regulator is indifferent between being informed or uninformed about the incumbent's true costs.

In this case, he would be willing to set fee t_1^L under all degrees of information, as shown in figure 4.[18]

Costly monitoring. If the monitoring costs of implementing emission fees are relatively high, regulators could alternatively achieve similar objectives by setting instead an indirect tax on sales of polluting goods. This strategy might be specifically attractive if the existing sale tax is difficult to evade. In the case of an indirect tax, the regulator would be charging a fee t_1 in the first period or t_2 in the second period to the seller of the good rather than the polluting producer. Such an indirect tax would, hence, disincentivize the consumption (and thus production) of the polluting good in the same amount as the emission fee directly charged to the original producer. In addition, for given parameter values, this indirect tax is constant in output.

5.1 Extensions

Persistence of incomplete information. Our model considers that, as in other signaling games, uninformed agents can observe the incumbent's costs during the second stage of the game; see, for instance, Milgrom and Roberts (1986), Harrington (1987) or Schultz's (1999). Importantly, this allows the regulator to be able to induce socially optimal output levels as in a complete information context, thus eliminating inefficiencies during the second stage. If, however, the regulator remained as uninformed as in the first period, environmental policy would induce inefficiencies, both with and without entry. Nevertheless, since the regulator is informed about the production costs of one firm (entrant), emission fees under entry would generate smaller inefficiencies than those under no entry. In particular, the inefficiencies under duopoly would only originate from the incumbent's production (which is smaller than its output when entry does not ensue), while under monopoly they would stem from the incumbent's output level. As a consequence, the regulator would be less attracted to facilitate the incumbent's entry-deterring practices when he remains uninformed than when he becomes perfectly informed. In contrast, if his information accuracy improves during the second period, i.e., β approaches one of its extreme values (0 or $+\infty$), entry deterrence will be sustained under less restrictive parameter conditions. This result, hence, complements one of the policy implications discussed above: first, environmental agencies which are well informed about industry characteristics before setting emission fees would hinder incumbent's entry-deterring behavior. However, if these agencies are initially poorly informed, their role as facilitators of entry deterrence can only be diminished by, actually, maintaining the agencies as poorly informed as they initially are. Intuitively, this occurs because of the inefficiencies that their entry-deterring regulation might originate in an uncertain context. If, instead, after being uninformed in the first stage they become perfectly informed, agencies would have the highest incentives to facilitate the incumbent's entry-deterring practices, i.e., the pooling equilibrium would be sustained under larger parameter conditions than in any of the above contexts. Graphically, a better information accuracy

[18] When priors are sufficiently high, the regulator anticipates that the separating PBE ensues and, as shown in figure 3, he prefers to be perfectly informed. In this context, he can induce socially optimal output levels, thus hindering the emergence of inefficiencies.

during the second period would produce a downward shift in cutoff $\overline{F}(\beta)$ on figure 4, thus expanding the region under which entry deterrence emerges.

Clean entrants. Alternatively, our model could be augmented to consider that firms' production, rather than generating the same environmental damage, imposes different damages; using, for instance, a damage function $ED = d(x_{inc} + \alpha x_{ent})^2$, where $\alpha \in (0,1)$ indicates that the technology of the potential entrant is cleaner than that of the incumbent. In such a setting, the model would need to be further enlarged since, in order to induce socially optimal output levels, the regulator would require a type-dependent fee (one to the more polluting incumbent and another to the cleaner newcomer). Interestingly, in this context the regulator would have fewer incentives to facilitate the incumbent's entry-deterring practices for two reasons: first, the potential entrant, anticipating a less-stringent emission fee, would be attracted to the industry under larger parameter conditions. Second, the welfare level that arises under the entry of the clean newcomer is higher than that under no entry; where the dirtier incumbent maintains its monopoly power.[19] As a consequence, the development of cleaner technologies by the potential entrant would diminish the ability of environmental policy to serve as a support for the incumbent's entry-deterring practices. Graphically, in terms of figure 4, the cutoff $\overline{F}(\beta)$ would increase, thus shrinking the entry-deterring region, as the potential entrant becomes cleaner, i.e., α approaches zero.

Convex production costs. Our model considers linear production costs. However, assuming convex costs, e.g., $c_j^K \cdot q^2$ for every firm $j = \{inc, ent\}$, would not qualitatively affect our main results. Appendix 2 explores this setting in detail, but we next summarize its main differences with respect to linear costs. In particular, under complete information, unregulated firms would have incentives to produce a larger output level (and thus generate more pollution) when costs are convex than linear, ultimately leading the regulator to impose a more stringent fee; a result that applies across periods and both when entry occurs and when it does not. In the incomplete information game, the separating equilibrium also predicts larger output levels if firms are left unregulated and, as a consequence, environmental policy becomes more stringent when costs are convex than linear, i.e., fee t_1^* is larger under all parameter values. In addition, the pooling equilibrium can be sustained under more restrictive conditions when firms' costs are convex than linear. Specifically, cutoff $\overline{F}(\beta)$ experiences an upward shift, implying that the region of entry costs for which the regulator facilitates the incumbent's entry-deterring practices, $F > \overline{F}(\beta)$, shrinks. Intuitively, this occurs because a given increase in the first-period emission fee t_1^H (which induces the high-cost incumbent to produce the socially optimal output $q^{H,SO}$) produces a larger deviation (and thus entails a larger inefficiency) when production costs are convex than linear, ultimately dissuading the regulator from supporting the incumbent's concealment of information.[20] Finally, similar as in the

[19] Note that this result is different from that in the paper, whereby firms' symmetry leads the regulator to induce duopolists to produce the same output level q_{SO}^K as a monopolist would, ultimately generating the same welfare level with and without entry.

[20] The inefficiencies of setting an entry-deterring emission fee can be evaluated by the elasticity of the monopolist's output function to a marginal increase in emission fees above the socially optimal level. In particular, under convex costs this elasticity is $\varepsilon_{q^K(t_1),t_1} = \frac{1-2d}{2\left(1+c_{inc}^K\right)}$, whereas under linear costs it only is $\varepsilon_{q^K(t_1),t_1} = \frac{1}{2} - d$. For more details, see Appendix 2.

linear cost case, if the regulator becomes more poorly informed about the incumbent's high costs, i.e., higher β, cutoff $\overline{F}(\beta)$ shifts downwards. Therefore, the set of parameters in which regulation helps to support entry deterrence enlarges.

6 Conclusions

Our paper analyzes an entry-deterrence game in which a regulator sets emission fees without being able to perfectly observe the incumbent's costs. In particular, we examine how regulators with different informational advantages, relative to the potential entrant, can facilitate or hinder entry-deterring practices. We show that regulators who are perfectly informed only sustain the incumbent's behavior under a restrictive set of parameter conditions, i.e., if entry costs are sufficiently large compared to the inefficiencies arising from setting stringent emission fees. However, as regulators become poorly informed about the incumbent's costs, the expected welfare loss that emerges from inefficient fees is smaller, thus inducing the regulator to support the incumbent's entry-deterring behavior under larger conditions. In addition, we demonstrate that the regulator is willing to support the pooling equilibrium that deters entry regardless of the accuracy of his information if entry costs are sufficiently high.

Our model can be extended in several directions. First, we considered that the regulator receives costless reports that allowed him to potentially be better informed than the entrant. However, if these reports are costly, and such a cost is increasing in their accuracy, the equilibrium results presented in this paper could be sustained under different parameter conditions. Second, the regulator might experience a political cost from supporting entry-deterring practices when his information is imprecise. If this political cost enters into the social welfare function, our results could be affected. Finally, our model could consider different ex-ante priors for the regulator and entrant, i.e., q and p, respectively. For example, the regulator could initially be more pessimistic about the incumbent's costs being high than the entrant, i.e., $q < p$. In this setting, the regulator's report would entail a belief q^{β} that either: (1) maintains his initial pessimism, $q^{\beta} < p$; (2) reverts it, $q^{\beta} > p$; or (3) generates cases in which both players sustain the same beliefs, $q^{\beta} = p$. The emergence of any of these three cases depends on the initial prior asymmetry $q - p$, and on the curvature of the q^{β} function. Importantly, the difference between q^{β} and p would non-trivially affect the incentives of the regulator to support the incumbent's entry-deterring practices.

7 Appendix

7.1 Appendix 1 - General linear demand function

Let us separately analyze the complete information setting, and afterwards the separating and pooling equilibria in the incomplete information environment.

Complete information. *First period.* In this period, the incumbent monopolist maximizes $(a-bq)q - c_{inc}^K q - t_1 q$, and thus produces according to an output function $q^K(t_1) = \frac{a-\left(c_{inc}^K+t_1\right)}{2b}$. This output function increases in the vertical intercept of the inverse demand function, a, and as the demand function becomes steeper (larger values of b, graphically implying an inward pivoting effect on the demand function). The regulator's maximizes the social welfare function

$$\max_{q\geq 0} SW(q) = CS(q) + PS(q) + T_1 - ED(q)$$

which yields a socially optimal output $q_{SO}^K = \frac{a-c_{inc}^K}{2d+b}$, which is decreasing in the environmental damage of pollution, d, and on the incumbent's cost parameter, c_{inc}^K. Anticipating the production described in output function $q^K(t_1) = \frac{a-\left(c_{inc}^K+t_1\right)}{2b}$, the regulator sets a first-period emission fee, t_1^K, that solves $\frac{a-\left(c_{inc}^K+t_1\right)}{2b} = \frac{a-c_{inc}^K}{2d+b}$, i.e., $t_1^K = (2d-b)\frac{a-c_{inc}^K}{2d+b} = (2d-b)q_{SO}^K$, which is strictly positive as long as pollution is relatively damaging, i.e., $d > b/2$. Intuitively, note that as demand becomes flatter (low values of b), condition $d > b/2$ holds for most values of d, while if the demand is relatively steeper, such a condition is more difficult to satisfy. In this case, the market failure arising from the monopolist's market power becomes large and the regulator would have incentives to subsidize the monopolist's production in order to increase output for most values of d. However, the regulator would set emission fees if the environmental damage from pollution imposes a more severe welfare loss than the monopolist's market power, i.e., $d > b/2$.

Second period. In the second period, entry only occurs when the incumbent's costs are high. In this setting, incumbent and entrant simultaneously and independently maximize profits, thus selecting output function $x_j^H(t_2) = \frac{a-\left(c_j^H+t_2\right)}{3b}$ for every firm $j = \{inc, ent\}$ and emission fee t_2. Anticipating such output functions, the regulator sets t_2 in order to induce a socially optimal aggregate production, X_{SO}^H, which coincides with $q_{SO}^H = \frac{a-c_{inc}^H}{2d+b}$, i.e., fee $t_2^{H,E}$ solves

$$\frac{a-\left(c_{inc}^H+t_2\right)}{3b} + \frac{a-(c_{ent}+t_2)}{3b} = \frac{a-c_{inc}^H}{2d+b}.$$

In particular, $t_2^{H,E} = \frac{(4d-1)\left(a-c_{inc}^H\right)}{2(2d+b)}$, which can also be represented as $t_2^{H,E} = (4d-1)\frac{X_{SO}^H}{2}$. This fee induces every firm to produce half of the socially optimal output, i.e., $x_j^H(t_2^{H,E}) = \frac{X_{SO}^H}{2}$. (If the incumbent's costs are low, then entry does not ensue, and the incumbent maintains its monopoly power producing according to output function $x_{inc}^L(t_2) = \frac{a-\left(c_{inc}^L+t_2\right)}{2b}$. In this setting, the regulator sets a second-period emission fee that coincides with the first-period fee under monopoly, i.e., $t_2^{L,NE} = t_1^L$.)

Incomplete information-I. *Separating equilibrium.* As described in the proof of Proposition 1, the low-cost incumbent chooses an output level output function $q^A(t_1)$ that solves the incentive compatibility condition C1, thus yielding $q^A(t_1) = \frac{\left(a-c_{inc}^H\right)\left[(2d+b)-b\sqrt{3\delta}\right]}{2b} - \frac{t_1(2d+b)}{2b}$.

Given output function $q^A(t_1)$, we can replicate the regulator's problem about selecting emission fee t_1^* under incomplete information about the incumbent's costs (minimizing inefficiencies, as described in problem 5) which yields a relatively intractable expression for fee t_1^*. Nonetheless, for the parameters considered in the paper, its expression becomes

$$t_1^* = \frac{1}{20}\left[\frac{60a + 16bp^{\beta} - 15}{3+4b} + \frac{2\left(1+p^{\beta}\right)(9-20a)\,b}{(3+2b)} - 4\right]$$

This emission fee behaves as the analogous fee under linear production costs (and depicted in figure 2 of the paper): it increases in parameter β, and shifts upwards as the regulator becomes more certain about the incumbent's costs being low (i.e., as his prior p decreases). Figure A1 depicts emission fee t_1^*, and emphasizes the similarities with the setting in which the demand function is $p(q) = 1 - q$. However, relative to such a setting, fee t_1^* becomes more stringent as the demand function is more elastic. In particular, when parameter b decreases, the indirect demand function becomes flatter (for a given intercept a), thus increasing the monopolist's incentives to produce larger output levels. In order to curb such additional pollution, the regulator responds setting a more stringent fee t_1^*; as depicted in figure A1 with the upward shift in the emission fee from the case in which $b = 1$ to that in which $b = 1/8$.

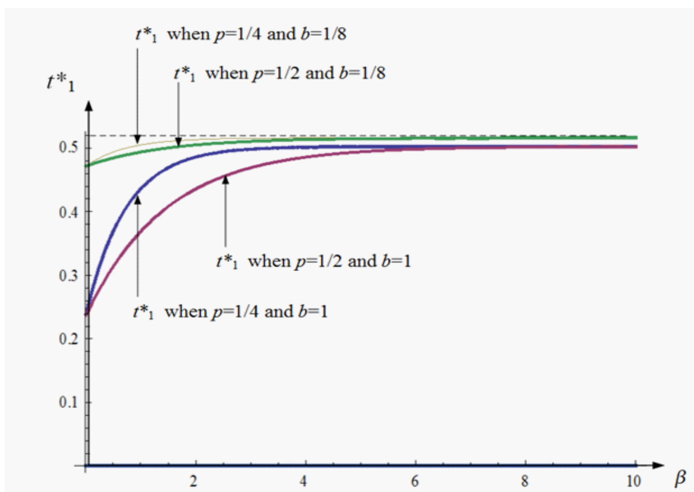

Fig A1. Emission fee t_1^* for different values of b.

Incomplete information-II. *Pooling equilibrium.* As described in Proposition 2, in the pooling equilibrium of the game the regulator sets on the high-cost incumbent the fee corresponding to the low-cost firm, t_1^L, and the high-cost firm responds mimicking the output level of the low-cost firm, $q^L\left(t_1^L\right)$, which ultimately conceals its type from the potential entrant and thus deters entry. The welfare benefit from deterring entry, namely, the savings in entry costs F, coincide in the model where the inverse demand function is $p(q) = 1 - q$ and that in which $p(q) = a - bq$. Hence, only the welfare cost from deterring entry, i.e., the inefficiencies arising from setting fee t_1^L, differ across models. We can therefore analyze the regulator's incentives to set a higher-than-optimal fee on the high-cost incumbent (higher than the fee t_1^H that would induce this firm to produce the socially optimal amount, i.e., $q^H\left(t_1^H\right) = q^{H,SO}$) by evaluating the incumbent's output reduction, i.e., its deviation from socially optimal production levels. Specifically, we can measure this inefficiency by using the elasticity of the monopolist's output function to a marginal increase in emission fees above the socially optimal level $q^{H,SO} = q^H\left(t_1^H\right)$, i.e.,

$$\varepsilon_{q^H(t_1),t_1} = \frac{\partial q^H(t_1)}{\partial t_1}\frac{t_1^H}{q^H\left(t_1^H\right)}.$$

In particular, under inverse demand function $p(q) = a - bq$, this elasticity becomes $\varepsilon_{q^H(t_1),t_1} = \frac{1}{2} - \frac{d}{b}$, whereas under $p(q) = 1 - q$ it is $\varepsilon_{q^K(t_1),t_1} = \frac{1}{2} - d$. Comparing these expressions, we can observe that, for demand functions steeper than $1 - q$, i.e., $b < 1$, the monopolist responds more strongly to a given increase in taxes when facing demand function $a - bq$ than $1 - q$. That is, cutoff $\overline{F}(\beta)$ experiences an upward shift, thus shrinking the entry-deterring region $F > \overline{F}(\beta)$. As a consequence, the regulator becomes less willing to facilitate the incumbent's entry-deterring practices. However, when the demand function is flatter than $1 - q$, i.e., $b > 1$, the monopolist responds by reducing its output to a lesser degree when facing demand function $a - bq$. In this case, cutoff $\overline{F}(\beta)$ shifts downwards, thus expanding the region for which the regulator supports the incumbent's entry-deterring behavior, i.e., $F > \overline{F}(\beta)$.

7.2 Appendix 2 - Convex production costs

We next examine how our equilibrium results would be affected by the consideration of convex, rather than linear, production costs, i.e., every firm j's costs become $c_j^K \cdot q^2$ where $c_j^H > c_j^L > 0$ and $j = \{inc, ent\}$. Let us separately analyze the complete information setting, and afterwards the separating and pooling equilibria in the incomplete information environment.

Complete information. *First period.* In this period, the incumbent monopolist maximizes $(1 - q)q - c_{inc}^K q^2 - t_1 q$, and thus produces according to an output function $q^K(t_1) = \frac{1-t_1}{2(1+c_{inc}^K)}$ Comparing this output function with that under linear costs, $\frac{1-(c_{inc}^K+t_1)}{2}$, we find the difference

$$\frac{1-t_1}{2(1+c_{inc}^K)} - \frac{1-(c_{inc}^K+t_1)}{2} = \frac{c_{inc}^K\left(c_{inc}^K+t_1\right)}{2\left(1+c_{inc}^K\right)},$$

which is positive for all parameter values. In particular, marginal costs are lower when the firm faces convex than linear costs, i.e., $2c_{inc}^K q < c_{inc}^K$ holds for all output levels satisfying $q < \frac{1}{2}$. Since, in addition, the profit maximizing output under both convex and linear costs satisfy $\frac{1}{2} > \frac{1-t_1}{2(1+c_{inc}^K)} > \frac{1-(c_{inc}^K+t_1)}{2}$, then we can conclude that, for every emission fee t_1, the incumbent captures a larger profit from each of the inframarginal units produced under convex costs, and thus has incentives to produce a larger output when its costs are convex than when they are linear.

The regulator's maximizes the social welfare function

$$\max_{q\geq 0} SW(q) = CS(q) + PS(q) + T_1 - ED(q)$$

which yields a socially optimal output $q^K_{SO} = \frac{1}{1+2d+2c^K_{inc}}$, which is decreasing in the environmental damage of pollution, d, and on the incumbent's cost parameter, c^K_{inc}. Anticipating the (relatively large) production described in output function $q^K(t_1) = \frac{1-t_1}{2\left(1+c^K_{inc}\right)}$, the regulator sets a first-period emission fee, t^K_1, that solves $\frac{1-t_1}{2\left(1+c^K_{inc}\right)} = \frac{1}{1+2d+2c^K_{inc}}$, i.e., $t^K_1 = \frac{2d-1}{1+2d+2c^K_{inc}} = (2d-1)q^K_{SO}$, which is strictly positive given the initial assumption $d > 1/2$. Comparing this emission fee with that under linear costs, $(2d-1)\frac{1-c^K_{inc}}{1+2d}$, we observe that the difference

$$\frac{2d-1}{1+2d+2c^K_{inc}} - (2d-1)\frac{1-c^K_{inc}}{1+2d} = \frac{(2d-1)\, c^K_{inc}\left(2d-1+2c^K_{inc}\right)}{(2d+1)\left(1+2d+2c^K_{inc}\right)}$$

is positive since $d > 1/2$ by definition. Intuitively, the regulator anticipates a larger output (and pollution) if the monopolist is left unregulated in the convex costs context and, as a consequence, sets a more stringent fee than when costs are linear in output.

Second period. In the second period, entry only occurs when the incumbent's costs are high. In this setting, incumbent and entrant simultaneously and independently maximize profits, thus selecting output function $x^H_j(t_2) = \frac{1-t_2}{3+2c^H_j}$ for every firm $j = \{inc, ent\}$ and emission fee t_2. Similarly as in the first period, output functions yield a larger production level under convex than linear costs, for all emission fee t_2 since the difference $\frac{1-t_2}{3+2c^H_{inc}} - \frac{1-\left(c^H_{inc}+t_2\right)}{3} = \frac{c^H_{inc}\left(1+2c^H_{inc}+2t_2\right)}{9+6c^H_{inc}}$ is positive under all parameters.

Anticipating such output functions, the regulator sets t_2 in order to induce a socially optimal aggregate production, X^H_{SO}, which coincides with $q^H_{SO} = \frac{1}{1+2d+2c^H_{inc}}$, i.e., fee $t^{H,E}_2$ solves

$$\frac{1-t_2}{3+2c^H_{inc}} + \frac{1-t_2}{3+2c_{ent}} = \frac{1}{1+2d+2c^H_{inc}}.$$

In particular, $t^{H,E}_2 = \frac{4d-1+2c^H_{inc}}{4d+2+4c^H_{inc}}$, thus inducing every firm to produce half of the socially optimal output, $x^H_j(t^{H,E}_2) = \frac{X^H_{SO}}{2}$. Alike under monopoly, in the case of duopoly the regulator also needs to set a more stringent emission fee when firms' costs are convex rather than linear in output since the difference

$$\frac{4d-1+2c^H_{inc}}{4d+2+4c^H_{inc}} - (4d-1)\frac{1-c^H_{inc}}{2(1+2d)} = \frac{c^H_{inc}\left[3-2d+8d^2+4(2d-1)c^H_{inc}\right]}{2\,(2d-1)\left(1+2d+2c^H_{inc}\right)}$$

is positive for all parameter values. (If the incumbent's costs are low, then entry does not ensue, the incumbent maintains its monopoly power producing with output function $x^L_{inc}(t_2) = \frac{1-t_2}{2\left(1+c^L_{inc}\right)}$; while the regulator sets a second-period emission fee that coincides with the first-period fee under monopoly, i.e., $t^{L,NE}_2 = t^L_1$.)

Incomplete information-I. *Separating equilibrium.* As described in the proof of Proposition 1, the low-cost incumbent increases its output level, from $q^L(t_1)$ under complete information to $q^A(t_1) > q^L(t_1)$, in order to guarantee that the high-cost incumbent does not have incentives to mimic it. In particular, output function $q^A(t_1)$ solves the incentive compatibility condition

$$M_{inc}^H(q^H(t_1), t_1) + \delta D_{inc}^H \geq M_{inc}^H(q^A(t_1), t_1) + \delta \overline{M}_{inc}^H,$$

where $M_{inc}^H(q(t_1), t_1)$ denotes its first-period monopoly profits when producing any output level $q(t_1)$; D_{inc}^H represents its second-period duopoly profits evaluated at the socially optimal emission fee $t_2^{H,E}$; and $\overline{M}_{inc}^H$ denotes the incumbent's second-period monopoly profits evaluated at the optimal fee $t_2^{H,NE}$. Solving for output function $q^A(t_1)$ yields $q^A(t_1) = \frac{(1-t_1)\left(1+2d+2c_{inc}^H\right)+\left(1+c_{inc}^H\right)\sqrt{3\delta}}{2\left(1+c_{inc}^H\right)\left(1+2d+2c_{inc}^H\right)}$.

Given output function $q^A(t_1)$, we can replicate the regulator's problem about selecting emission fee t_1^* under incomplete information about the incumbent's costs (minimizing inefficiencies, as described in problem 5) which yields a relatively intractable expression for fee t_1^*. Nonetheless, for the parameters considered in the paper, its expression becomes $t_1^* = \frac{34+435\sqrt{3}+\left(136-435\sqrt{3}\right)p^{\beta}}{68\left(15+2p^{\beta}\right)}$. This emission fee behaves as the analogous fee under linear production costs (and depicted in figure 2 of the paper): it increases in parameter β, and shifts upwards as the regulator becomes more certain about the incumbent's costs being low (i.e., as his prior p decreases). Figure A2a, which depicts emission fee t_1^*, emphasizes the similarities with the setting in which production costs are linear. However, relative to such a setting, fee t_1^* is more stringent when costs are convex since, following a similar argument as in the complete information context, the regulator seeks to curb the stronger incentives of the incumbent to produce when its costs are convex than when they are linear. Figure A2b depicts emission fee t_1^* under both linear and convex costs, illustrating its higher stringency when costs are convex.

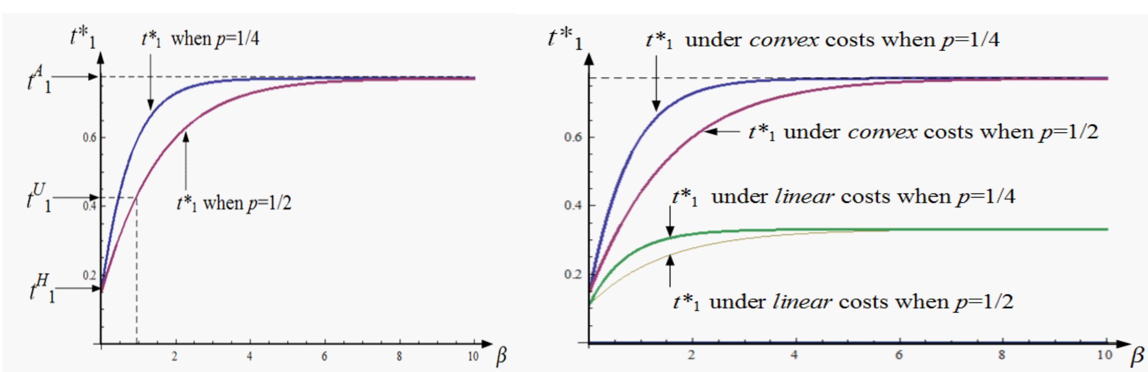

Fig A2a. Emission fee t_1^*.

Fig A2b. Emission fee t_1^* under linear vs. convex costs.

Incomplete information-II. *Pooling equilibrium.* Similarly as in the proof of Proposition 2, the high-cost incumbent might have incentives to mimic the higher production level of the low-cost firm during the first-period game (and thus conceal its type from the potential entrant, which is deterred from the industry). In particular, this occurs if, for emission fee t_1^L, the high-cost incumbent's profits from deterring entry, by choosing output level $q^L(t_1^L)$, are larger than its profits from selecting the complete-information output level $q^H(t_1^L)$ that, while attracting entry, maximizes its first-period profits. That is, if $M_{inc}^H(q^L(t_1^L), t_1') + \delta \overline{M}_{inc}^H \geq M_{inc}^H(q^H(t_1^L), t_1^L) + \delta D_{inc}^H$.

Regarding the uninformed regulator, he yields a welfare $SW^{H,NE}(t_1^L, t_2^{H,NE})$ by selecting a fee t_1^L. If, instead, he deviates to any off-the-equilibrium fee $t_1'' \neq t_1^L$, the incumbent anticipates it will not be able to conceal its type from the potential entrant, thus responding with its complete-information output, $q^H(t_1'')$, and entry ensues. In this context, the regulator obtains $SW^{H,E}(t_1'', t_2^{H,E})$, which is maximized at the emission fee $t_1'' = t_1^*$ that minimizes the regulator's informational inefficiencies (from problem 5). Solving for entry costs, F, in $SW^{H,NE}(t_1^L, t_2^{H,NE}) = SW^{H,E}(t_1^*, t_2^{H,E})$ yields an intractable expression for cutoff $\overline{F}(\beta)$. However, in order to facilitate the comparison with the environment in which costs are linear, figure A2c depicts this cutoff evaluated at the parameter values considered throughout the paper.

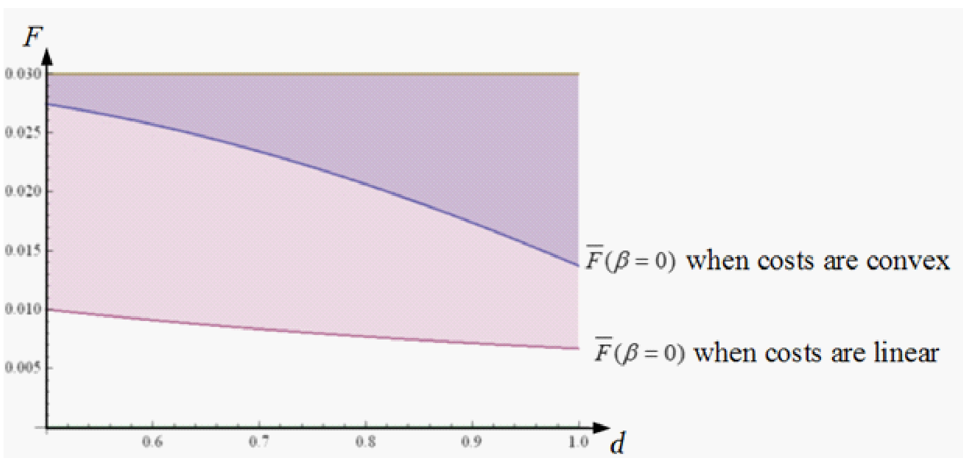

Fig A2c. Entry costs sustaining the Pooling PBE.

Figure A2c indicates that the region of entry costs in which the regulator facilitates the incumbent's entry-deterring practices by setting an emission fee t_1^L, i.e., $F > \overline{F}(\beta)$, is smaller when production costs are convex (dark shaded area) than when they are linear (sum of dark and light shaded areas). Intuitively, this occurs because setting a larger-than-optimal emission fee, such as t_1^L on the high-cost incumbent, produces a larger reduction in this firm's output when its production costs are convex than when they are linear. As a consequence, the use of environmental policy as an entry-deterring tool yields larger inefficiencies under convex costs, and ultimately limits the regulator's willingness to deter entry.

We can more formally prove the above result under all parameter conditions by examining the elasticity of the monopolist's output function to a marginal increase in emission fees above the socially optimal level $q^{K,SO} = q^K\left(t_1^K\right)$, i.e.,

$$\varepsilon_{q^K(t_1),t_1} = \frac{\partial q^K(t_1)}{\partial t_1}\frac{t_1^K}{q^K\left(t_1^K\right)}.$$

In particular, under convex costs, this elasticity becomes $\varepsilon_{q^K(t_1),t_1} = \frac{1-2d}{2\left(1+c_{inc}^K\right)}$, whereas under linear costs it is $\varepsilon_{q^K(t_1),t_1} = \frac{1}{2} - d$, with the difference $\frac{1-2d}{2\left(1+c_{inc}^K\right)} - \left(\frac{1}{2} - d\right) = \frac{(2d-1)c_{inc}^K}{2\left(1+c_{inc}^K\right)}$ being positive under all parameter values given that $d > 1/2$ by assumption. Therefore, for a given deviation from the emission fee $t_1^{K,SO}$ that in the first period yields the socially optimal output $q^{K,SO}$, the regulator entails larger deviations from $q^{K,SO}$ (and thus larger inefficiencies) when firms' costs are convex than when they are linear.

Finally, figure A2d depicts how cutoff $\overline{F}(\beta)$ decreases in β, thus exhibiting a similar pattern as when production costs are linear (illustrated in figure 4), i.e., the pooling equilibrium can be sustained under larger parameter values when the regulator has access to less accurate information.

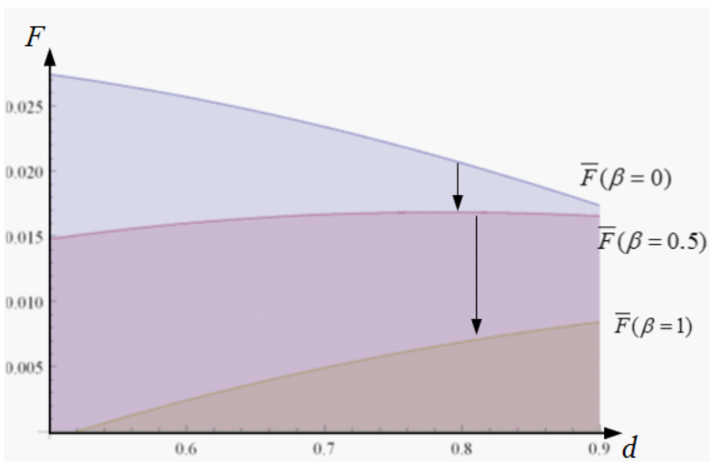

Figure A2d. Effect of β on the pooling PBE.

7.3 *Proof of Proposition 1*

Incumbents. We next demonstrate that, for a given fee t_1, the high-cost incumbent selects the same output function as under complete information, $q^H(t_1)$, since its overall profits exceed those from deviating towards the low-cost incumbent's output $q^{L,sep}(t_1)$, given that $M_{inc}^H(q^H(t_1), t_1) + \delta D_{inc}^H \geq M_{inc}^H(q^{L,sep}(t_1), t_1) + \delta \overline{M}_{inc}^H$, where $M_{inc}^H(q(t_1), t_1)$ denotes its first-period monopoly profits when producing any output level $q(t_1)$. D_{inc}^H represents its second-period duopoly profits evaluated at the socially optimal emission fee $t_2^{H,E}$ since the regulator perfectly observes the incumbent's costs in the second period and can redesign his environmental policy. Similarly, $\overline{M}_{inc}^H$ denotes the incumbent's second-period monopoly profits evaluated at the optimal fee $t_2^{H,NE}$. Rewriting the above incentive compatibility condition, we obtain

$$M_{inc}^{H}(q^{H}(t_1),t_1)-M_{inc}^{H}(q^{L,sep}(t_1),t_1)\geq \delta\left[\overline{M}_{inc}^{H}-D_{inc}^{H}\right] \tag{C1}$$

The low-cost incumbent, however, produces an output level, $q^{L,sep}(t_1)$, larger than under complete information, $q^{L}(t_1)$, in order to reveal its type to the potential entrant and deter entry. Since any deviations from $q^{L,sep}(t_1)$ induce entry, the most profitable deviation is $q^{L}(t_1)$. Therefore, the low-cost incumbent obtains larger profits from $q^{L,sep}(t_1)$ than $q^{L}(t_1)$ when $M_{inc}^{L}(q^{L,sep}(t_1),t_1)+\delta\overline{M}_{inc}^{L}\geq M_{inc}^{L}(q^{L}(t_1),t_1)+\delta D_{inc}^{L}$, or equivalently,

$$M_{inc}^{L}(q^{L}(t_1),t_1)-M_{inc}^{L}(q^{L,sep}(t_1),t_1)\leq \delta\left[\overline{M}_{inc}^{L}-D_{inc}^{L}\right] \tag{C2}$$

Conditions C1 and C2 hence identify a set of output functions $q^{L,sep}(t_1)\in\left[q^{A}(t_1),q^{B}(t_1)\right]$, where $q^{A}(t_1)$ solves C1 and $q^{B}(t_1)$ solves C2 with equality.

Regulator. If conditions C1-C2 are satisfied, the regulator, despite not perfectly observing the incumbent's type, is able to anticipate that the high-cost firm produces according to $q^{H}(t_1)$ while the low-cost incumbent chooses $q^{L,sep}(t_1)$. (In addition, it is easy to show that the low-cost firm selects the output function, $q^{L,sep}(t_1)=q^{A}(t_1)$, that entails the smallest deviation from its first-period output under complete information, $q^{L}(t_1)$, where $q^{A}(t_1)>q^{L}(t_1)$, and that $q^{A}(t_1)$ is indeed the only equilibrium output level that satisfies the Cho and Kreps' (1983) Intuitive Criterion; as we demonstrate below.) Hence, the regulator selects emission fee t_1 that minimizes the deadweight loss associated to his inaccurate information,

$$\min_{t_1\geq 0}\ p^{\beta}\left|DWL_{H}(t_1)\right|+\left(1-p^{\beta}\right)\left|DWL_{L}(t_1)\right|$$

Let us first focus on the inefficiencies arising when the incumbent's type is high, as captured by $DWL_{H}(t_1)\equiv\int_{q^{H}(t_1)}^{q_{SO}^{H}}\left[MB^{H}(q)-MD(q)\right]dq$. As described in section 3, $q_{SO}^{H}\equiv\frac{1-c_{inc}^{H}}{1+2d}$ represents the socially optimal output level, and $q^{H}(t_1)=\frac{1-c_{inc}^{H}-t_1}{2}$ denotes the output function that maximizes the high-cost incumbent's profits. In addition, the benefit from a marginal increase in output is $MB^{H}(q)=(1-q)-c_{inc}^{H}$, whereas its associated marginal environmental damage is $MD(q)=2dq$. Integrating, we obtain

$$DWL_{H}(t_1)=\frac{\left[1-2d(1-t_1)+t_1-(1-2d)c_{inc}^{H}\right]^2}{8\rho}$$

where $\rho\equiv 1+2d$. Similarly operating for the case in which the incumbent's costs are low, where $q_{SO}^{L}\equiv\frac{1-c_{inc}^{H}}{1+2d}$, we find

$$DWL_{L}(t_1)=\frac{\left[1-2d(1-t_1)+t_1-\gamma+(\gamma+\rho)c_{inc}^{H}-2c_{inc}^{L}\right]^2}{8\rho}$$

where $\gamma \equiv \sqrt{3\delta}$. Taking into account that $DWL_H(t_1)$ and $DWL_L(t_1)$ are both positive, the regulator can now find the expected deadweight loss $p^\beta DWL_H(t_1) + \left(1-p^\beta\right) DWL_L(t_1)$. Taking first order conditions with respect to t_1, we find

$$t_1^* \equiv \frac{2d-1+\gamma(1-p^\beta)+\left[p^\beta(2+\gamma)-\rho-\gamma\right]c_{inc}^H+2(1-p^\beta)c_{inc}^L}{\rho}$$

Emission fee t_1^* yields the minimum of the objective function $p^\beta\left|DWL_H(t_1)\right|+\left(1-p^\beta\right)\left|DWL_L(t_1)\right|$ since such function is convex in t_1, i.e., $\frac{\partial^2\left[p^\beta|DWL_H(t_1)|+\left(1-p^\beta\right)|DWL_L(t_1)|\right]}{\partial t_1^2}=\frac{\rho}{4}>0$ for all parameter values. Furthermore, fee t_1^* can be expressed as a linear combination of the socially optimal fees that the regulator would select if he was perfectly informed about the incumbent's costs being high, t_1^H, where t_1^H solves $q^H(t_1)=q_{SO}^H$, and its costs being low, t_1^A, where fee t_1^A solves $q^A(t_1)=q_{SO}^L$. Specifically, the weights on fees t_1^H and t_1^A can be found by solving for α in $t_1^*=\alpha t_1^H+(1-\alpha)t_1^A$, where weight $\alpha=p^\beta$, thus implying $t_1^*=p^\beta t_1^H+\left(1-p^\beta\right)t_1^A$. Therefore, emission fee t_1^* satisfies $t_1^H<t_1^*<t_1^A$. From the analysis of emission fee t_1^A in Lemma 2 in Espinola-Arredondo and Munoz-Garcia (2013), we know that it induces positive output levels as long as firms' costs are not extremely asymmetric, i.e., $c_{inc}^L<c_{inc}^H<\frac{\gamma+\rho c_{inc}^L}{\gamma+\rho}$. Hence, a less stringent fee t_1^* must also yield positive production levels. Finally, note that evaluating t_1^* at $\beta=1$ (when the regulator is as uninformed as the entrant), we find $t_1^U \equiv \frac{2d-1+[p(2+\gamma)-\rho-\gamma]c_{inc}^H+\left(2c_{inc}^L+\gamma\right)(1-p)c_{inc}^L}{\rho}$.

In particular, when $t_1^*<t_1^U$, the high-cost incumbent anticipates that if it deviates from $q^H(t_1)$ to $q^A(t_1)$ then the entrant's beliefs are $\mu\left(c_{inc}^H|q^A(t_1^*),t_1^*\right)=\mu'$. Therefore, entry is deterred if

$$\mu' D_{ent}^H+(1-\mu')D_{ent}^L-F<0$$

solving for μ', we obtain $\mu'<\frac{F-D_{ent}^L}{D_{ent}^H-D_{ent}^L}\equiv\overline{p}$. In contrast, when $t_1^*>t_1^U$, a deviation from $q^H(t_1)$ to $q^A(t_1)$ makes the entrant believe that the incumbent's costs are low, thus deterring entry. Similarly, when $t_1^*=t_1^U$, the entrant only relies on the incumbent's output level in order to infer its costs. Hence, after observing $q^A(t_1)$ it stays out.

Intuitive Criterion: Let us now show that the separating equilibrium where the low-cost incumbent chooses any first-period output function $q^{L,sep}(t_1)\neq q^A(t_1)$ violates the Cho and Kreps' (1983) Intuitive Criterion, and afterwards demonstrate that only $q^{L,sep}(t_1)=q^A(t_1)$ survives this equilibrium refinement. Consider the case where the low-cost incumbent chooses a first-period output function of $q^B(t_1)$. Let us check if a deviation towards $q(t_1)\in(q^A(t_1),q^B(t_1))$ is equilibrium dominated for either type of incumbent. On one hand, the high-cost incumbent can obtain the highest profit by deviating towards $q(t_1)\in(q^A(t_1),q^B(t_1))$ when entry does not follow. In such a case, the high-cost incumbent obtains $M_{inc}^H(q(t_1),t_1)+\delta\overline{M}_{inc}^H$ which exceeds its equilibrium profits if $M_{inc}^H(q(t_1),t_1)+\delta\overline{M}_{inc}^H>M_{inc}^H(q^H(t_1),t_1)+\delta D_{inc}^H$. However, condition C1 guarantees that this inequality does not hold for any $q(t_1)\in(q^A(t_1),q^B(t_1))$. Hence, the high-cost incumbent does not have incentives to deviate from $q^H(t_1)$ to $q(t_1)\in(q^A(t_1),q^B(t_1))$.

On the other hand, the low-cost incumbent can obtain the highest profit by deviating towards

$q(t_1) \in (q^A(t_1), q^B(t_1))$ when entry does not follow. In such case, the low-cost incumbent's payoff is $M^L_{inc}(q(t_1), t_1) + \delta\overline{M}^L_{inc}$, which exceeds its equilibrium profits of $M^L_{inc}(q^B(t_1), t_1) + \delta\overline{M}^L_{inc}$ since $M^L_{inc}(q(t_1), t_1) + \delta\overline{M}^L_{inc}$ reaches its maximum at $q^L(t_1)$ and $q^L(t_1) < q^B(t_1)$. Therefore, the low-cost incumbent has incentives to deviate from $q^B(t_1)$ to $q(t_1) \in (q^A(t_1), q^B(t_1))$. Hence, the entrant concentrates its posterior beliefs on the incumbent's costs being low, i.e., $\mu(c^H_{inc}|q(t_1), t_1) = 0$, and does not enter after observing a first-period output of $q(t_1) \in (q^A(t_1), q^B(t_1))$. Thus, the low-cost incumbent deviates from $q^B(t_1)$, and the informative equilibrium in which it selects $q^B(t_1)$ violates the Intuitive Criterion. A similar argument is applicable for all informative equilibria in which the low-cost incumbent selects $q(t_1) \in (q^A(t_1), q^B(t_1)]$, concluding that all of them violate the Intuitive Criterion.

Finally, let us check if the informative equilibrium in which the low-cost incumbent chooses $q^A(t_1)$ survives the Intuitive Criterion. If the low-cost incumbent deviates towards $q(t_1) \in (q^A(t_1), q^B(t_1)]$, the highest profit that it can obtain is $M^L_{inc}(q(t_1), t_1) + \delta\overline{M}^L_{inc}$, which is lower than its equilibrium payoff of $M^L_{inc}(q^A(t_1), t_1) + \delta\overline{M}^L_{inc}$. If instead, it deviates towards $q(t_1) < q^A(t_1)$, it obtains $M^L_{inc}(q(t_1), t_1) + \delta\overline{M}^L_{inc}$, which exceeds it equilibrium profit for all $q(t_1) \in [q^L(t_1), q^A(t_1))$. Hence, the low-cost incumbent has incentives to deviate. Let us now examine whether the high-cost incumbent also has incentives to deviate. The highest profit that it can obtain by deviating towards $q(t_1) \in (q^A(t_1), q^B(t_1)]$ is $M^H_{inc}(q(t_1), t_1) + \delta\overline{M}^H_{inc}$, which exceeds its equilibrium profit if $M^H_{inc}(q(t_1), t_1) + \delta\overline{M}^H_{inc} > M^H_{inc}(q^H(t_1), t_1) + \delta D^H_{inc}$. This condition can be rewritten as

$$\delta\left[\overline{M}^H_{inc} - D^H_{inc}\right] > M^H_{inc}(q^H(t_1), t_1) - M^H_{inc}(q(t_1), t_1)$$

which is satisfied for all $q(t_1) < q^A(t_1)$ from condition C1. Hence, the high-cost incumbent also has incentives to deviate towards $q(t_1) \in [q^L(t_1), q^A(t_1))$.

This implies that, after a deviation in $q(t_1) \in [q^L(t_1), q^A(t_1))$, the entrant cannot update its prior beliefs, and chooses to enter if its expected profit from entering satisfies $p \times D^H_{ent} + (1-p) \times D^L_{ent} - F > 0$ or $p \geq \frac{F - D^L_{ent}}{D^H_{ent} - D^L_{ent}} \equiv \overline{p}$, where $\overline{p} > 0$ for all $F > D^L_{ent}$ and $\overline{p} < 1$ for all $F < D^H_{ent}$. Hence, if $p \geq \overline{p}$, entry occurs, yielding profits of $M^L_{inc}(q(t_1), t_1) + \delta D^L_{inc}$ for the low-cost incumbent. Such profits are lower than its equilibrium profits $M^L_{inc}(q^A(t_1), t_1) + \delta\overline{M}^L_{inc}$. Therefore, the low-cost incumbent does not deviate from $q^A(t_1)$. Regarding the high-cost incumbent, it obtains profits $M^H_{inc}(q(t_1), t_1) + \delta D^H_{inc}$ by deviating towards $q(t_1)$, which are below its equilibrium profits $M^H_{inc}(q^H(t_1), t_1) + \delta D^H_{inc}$ since $q^H(t_1)$ is the argmax of $M^H_{inc}(q(t_1), t_1) + \delta D^H_{inc}$. Hence, the high-cost incumbent does not deviate towards $q(t_1)$ either, and this equilibrium survives the Intuitive Criterion for $p > \overline{p}$. In contrast, if $p < \overline{p}$, then entry does not occur, yielding profits $M^L_{inc}(q(t_1), t_1) + \delta\overline{M}^L_{inc}$ for the low-cost incumbent, which exceed its equilibrium profits $M^L_{inc}(q^A(t_1), t_1) + \delta\overline{M}^L_{inc}$ since $q(t_1) \in [q^L(t_1), q^A(t_1))$. Then, the separating equilibrium in which the low-cost incumbent selects $q^A(t_1)$ violates the Intuitive Criterion if $p < \overline{p}$. ■

7.4 *Proof of Corollary 1*

Differentiating t_1^* with respect to β, we obtain

$$\frac{\partial t_1^*}{\partial \beta} = \frac{p^\beta \ln(p) \left[2(c_{inc}^H - c_{inc}^L) - (1 - c_{inc}^H)\gamma\right]}{\rho}$$

and, since $p^\beta > 0$, $\ln(p) < 0$, and $\rho > 0$, $\frac{\partial t_1^*}{\partial \beta}$ becomes positive if and only if $2(c_{inc}^H - c_{inc}^L) - (1 - c_{inc}^H)\gamma < 0$ or, alternatively, $c_{inc}^H < \frac{2+\gamma-2(1-c_{inc}^L)}{2+\gamma}$. Comparing this condition with that on positive output levels and emission fees under complete information, i.e., $c_{inc}^H < \frac{1+2dc_{inc}^L}{\rho}$, we obtain that both cutoffs reach $c_{inc}^H = 1$ when $c_{inc}^L = 1$, but $\frac{2+\gamma-2(1-c_{inc}^L)}{2+\gamma}$ originates at $\frac{\gamma}{2+\gamma}$, while $\frac{1+2dc_{inc}^L}{\rho}$ originates at $\frac{1}{\rho}$, which is equivalent to $\frac{1}{1+2d}$. Since $\frac{\gamma}{2+\gamma} > \frac{1}{1+2d}$ for all $d > \frac{1}{\sqrt{3}} \simeq 0.57$, then cutoff $\frac{2+\gamma-2(1-c_{inc}^L)}{2+\gamma}$ lies above $\frac{1+2dc_{inc}^L}{\rho}$ for all $d \in \left(\frac{1}{\sqrt{3}}, 1\right]$, but below otherwise.

Furthermore, evaluating the emission fee t_1^* at $\beta = 0$, we obtain $\frac{(2d-1)(1-c_{inc}^H)}{\rho}$, while evaluating it at $\beta = 1$, we find $\frac{2d-1+[p(2+\gamma)-\rho-\gamma]c_{inc}^H+\left(2c_{inc}^L+\gamma\right)(1-p)c_{inc}^L}{\rho}$. Finally, $\lim_{\beta\to+\infty} t_1^* = \frac{(1-c_{inc}^H)(\rho+\gamma)-2(1-c_{inc}^L)}{\rho}$. ■

7.5 *Proof of Corollary 2*

Separating equilibrium vs. Complete information. When the incumbent's costs are low, the regulator induces the socially optimal output under complete information by setting the fee t_1^L that solves $q^L(t_1) = q_{SO}^L$. However, under the separating equilibrium, the low-cost incumbent produces according to output function $q^A(t_1)$, which satisfies $q^A(t_1) > q^L(t_1)$ for all t_1. If the regulator was perfectly informed about facing a low-cost incumbent, he would set a fee t_1^A that solves $q^A(t_1) = q_{SO}^L$. However, since the regulator is uninformed about the exact costs of the incumbent, he sets a fee that solves problem (5), i.e., t_1^*, which is less stringent than t_1^A, since it can be alternatively expressed as $t_1^* = p^\beta t_1^H + \left(1 - p^\beta\right) t_1^A$. Hence, the output level in the separating equilibrium, $q^A(t_1^*)$, exceeds the socially optimal output, q_{SO}^L, and entails inefficiencies.

When the incumbent's costs are high, the regulator also induces the socially optimal output q_{SO}^H by setting the fee t_1^H that solves $q^H(t_1) = q_{SO}^H$. In the separating equilibrium, while the high-cost firm also produces according to $q^H(t_1)$, the regulator does not set fee t_1^H, which would induce a socially optimal output, but instead sets fee t_1^*, which is more stringent than t_1^H, given that $t_1^* = p^\beta t_1^H + \left(1 - p^\beta\right) t_1^A$. As a consequence, output level $q^H(t_1^*)$ arises, which lies below $q^H(t_1^H) = q_{SO}^H$, thus entailing inefficiencies. Therefore, the introduction of incomplete information yields first-period output inefficiencies both when the incumbent's costs are high and low, thus entailing an overall welfare loss. In the second period, however, no inefficiencies arise, given that the regulator becomes perfectly informed about the incumbent's costs.

Separating equilibrium with and without regulator. Without regulation, the low-cost incumbent sets its first-period output function at $q^A(0)$. When the regulator is present, however, first-period output decreases to $q^A(t_1^*)$, where

$$q^A(0) > q^A(t_1^*) > q^A(t_1^A) = q_{SO}^L,$$

while when the incumbent's costs are high, this firm sets a first-period output of $q^H(0)$, while the regulator would set a fee t_1^* that induces this firm to produce a lower output level $q^H(t_1^*)$, since $q^H(t_1^*) < q^H(t_1^H) = q_{SO}^H < q^H(0)$.

In the second period, output is $x_{inc}^{K,NE}(t_2^{K,NE})$, which is socially optimal since fee $t_2^{K,NE}$ solves $x_{inc}^{K,NE}(t_2) = q_{SO}^K$. Therefore, the presence of the regulator ameliorates the environmental externality in the first period, and fully corrects inefficiencies in the second period, ultimately implying that his presence entails a welfare improvement. ■

7.6 *Proof of Proposition 2*

In the pooling strategy profile, the regulator sets a type-independent emission fee t_1' and the incumbent chooses a type-independent first-period output function $q(t_1)$ for any emission fee t_1. After observing equilibrium fee t_1' and output level $q(t_1')$ entrant's equilibrium beliefs cannot be updated, i.e., $\mu(c_{inc}^H|q(t_1'), t_1') = p$, which leads the potential entrant to enter as long as its expected profit from entering satisfies $p \times D_{ent}^H + (1-p) \times D_{ent}^L - F > 0$ or $p > \frac{F - D_{ent}^L}{D_{ent}^H - D_{ent}^L} \equiv \overline{p}$, where $\overline{p} \in (0,1)$ by definition. Note that if $p > \overline{p}$, entry occurs when t_1' and $q(t_1')$ are selected, which cannot be optimal for both types of incumbent, inducing them to select $q^K(t_1')$. But since $q^H(t_1') \neq q^L(t_1')$ this strategy cannot be a pooling equilibrium. Thus, it must be that $p \leq \overline{p}$, inducing the entrant to stay out.

Hence, the high-cost incumbent responds to emission fee t_1' with output level $q(t_1')$, as prescribed, if and only if its profits from deterring entry are larger than the profits it would make by selecting output level $q^H(t_1')$ that, while attracting entry, maximizes its first-period profits. That is, if $M_{inc}^H(q(t_1'), t_1') + \delta \overline{M}_{inc}^H \geq M_{inc}^H(q^H(t_1'), t_1') + \delta D_{inc}^H$, or alternatively

$$\delta \left[\overline{M}_{inc}^H - D_{inc}^H \right] \geq M_{inc}^H(q^H(t_1'), t_1') - M_{inc}^H(q(t_1'), t_1') \tag{C3}$$

and similarly for the low-cost incumbent, who selects output level $q(t_1')$, rather than deviating to its complete information output $q^L(t_1')$, if $M_{inc}^L(q(t_1'), t_1') + \delta \overline{M}_{inc}^L \geq M_{inc}^L(q^L(t_1'), t_1') + \delta D_{inc}^L$, or alternatively

$$\delta \left[\overline{M}_{inc}^L - D_{inc}^L \right] \geq M_{inc}^L(q^L(t_1'), t_1') - M_{inc}^L(q(t_1'), t_1') \tag{C4}$$

Let us now examine the regulator's incentives to choose a type-independent emission fee t_1'. When the incumbent's costs are high, the uninformed regulator yields a welfare $SW^{H,NE}(t_1', t_2^{H,NE})$ by selecting t_1'. If, instead, he deviates to any off-the-equilibrium fee $t_1'' \neq t_1'$, the incumbent selects $q^H(t_1'')$ and entry ensues. Hence, he obtains $SW^{H,E}(t_1'', t_2^{H,E})$, which is maximized at the emission fee $t_1'' = t_1^*$ that minimizes the regulator's informational inefficiencies. Thus, the regulator chooses the equilibrium fee t_1' if

$$SW^{H,NE}(t_1', t_2^{H,NE}) \geq SW^{H,E}(t_1^*, t_2^{H,E}). \tag{C5}$$

which holds if the savings in entry costs that arise from setting fee t_1' offset its associated inefficiency (relative to fee t_1^*).

In addition, using a similar argument as in Lemma 3 of Espinola-Arredondo and Munoz-Garcia (2013), it is straightforward to show that only the output function $q(t_1) = q^L(t_1)$, entailing an output level $q^L(t_1')$, survives the Cho and Kreps' (1987) Intuitive Criterion. Given this output function, it is also easy to show that the only equilibrium fee t_1' that, satisfying condition C5, survives the Intuitive Criterion, i.e., entails the minimum separation for the regulator, is fee $t_1' = t_1^L$. In particular, for the functional forms in the paper, condition C3 for the high-cost incumbent (evaluated at the equilibrium fee t_1^L and output level $q^L(t_1^L)$) holds for all $c_{inc}^H < \alpha_1$. Similarly, condition C5 for the regulator (evaluated at the equilibrium fee t_1^L and output $q^L(t_1^L)$) holds for all entry costs $F > \frac{\sqrt{\delta}\lambda\left(4\sqrt{3}\omega - 3\sqrt{\delta}\lambda\right) + \left(2p^\beta - p^{2\beta}\right)\left(\gamma^2\lambda^2 - 4\gamma\lambda\omega + 4\omega^2\right)}{8\delta\rho} \equiv \overline{F}(\beta)$, where $\lambda \equiv \left(1 - c_{inc}^H\right)$ and $\omega \equiv \left(c_{inc}^H - c_{inc}^L\right)$. This condition on entry costs is, however, compatible with the set of admissible entry costs, $D_{ent}^H > F > D_{ent}^L$, if $D_{ent}^H > \overline{F}(\beta)$, which is satisfied when $c_{inc}^H < \frac{2\left(1-c_{inc}^L\right)\left[\rho(3+\eta+6d\tau)\delta\right]^{1/2} + 4\rho\eta c_{inc}^L + 2\gamma\rho\tau(1+c_{inc}^L)}{4\gamma\rho + (5+6d)\delta - \rho p^\beta(4+4\gamma+3\delta)\left(2-p^\beta\right)} \equiv \alpha_2$, where $\eta \equiv p^\beta\left(p^\beta - 2\right)$ and $\tau \equiv \left(p^\beta - 1\right)^2$. In addition, $\alpha_2 < \alpha_1$ implying that the condition $c_{inc}^H < \alpha_2$ is more restrictive than $c_{inc}^H < \alpha_1$ for all $d > 1/2$. ■

7.7 *Proof of Corollary 3*

Pooling equilibrium vs. Complete information. When the incumbent's costs are low, the regulator induces the socially optimal output under complete information by setting the fee t_1^L that solves $q^L(t_1) = q_{SO}^L$. Under the pooling equilibrium, the regulator sets the type-independent fee t_1^L and the low-cost incumbent responds producing according to output function $q^L(t_1)$, which yields a socially optimal output.

When the incumbent's costs are high, the regulator sets a fee t_1^H under a complete information setting, and the incumbent responds with output function $q^H(t_1)$, which entails $q^H(t_1^H) = q_{SO}^H$, generating a social welfare of $W_{PE}^{H,R} \equiv \frac{1-\left(c_{inc}^L\right)^2 + \delta\left[1+\left(c_{inc}^H\right)^2\right] - 2c_{inc}^H\left(1+\delta-c_{inc}^L\right)}{2\rho}$. However, in the pooling equilibrium, the regulator chooses the type-independent fee t_1^L and the firm responds with $q^L(t_1)$, which generate an output level $q^L(t_1^L) \neq q_{SO}^H$, thus giving rise to inefficiencies that are partially offset by the saving in entry costs. In particular, social welfare in this context is $W_{CI}^{H,R} \equiv \frac{(1+\delta)\left[1+(c_{inc}^H-2)c_{inc}^H\right] - 2F\delta\rho}{2\rho}$. Comparing $W_{PE}^{H,R}$ and $W_{CI}^{H,R}$, we obtain that $W_{PE}^{H,R} > W_{CI}^{H,R}$ for all $F > \frac{\omega^2}{2\delta\rho}$, where $\frac{\omega^2}{2\delta\rho}$ coincides with cutoff $\overline{F}(\beta = 0)$.

Pooling equilibrium with and without regulator. Without regulation, the low-cost incumbent sets its first-period output function at $q^L(0)$. When the regulator is present, however, first-period output decreases to $q^L(t_1^L)$. When the incumbent's costs are high, this firm sets a first-period output of $q^L(0)$, while the regulator would set a fee t_1^L that induces this firm to produce a lower output level $q^L(t_1^L)$. In addition, since $q_{SO}^H = q^H(t_1^H) < q^L(t_1^L) < q^L(0)$, first-period output with regulator, $q^L(t_1^L)$, is closer to the socially optimal output q_{SO}^H than when the regulator is absent, $q^L(0)$. In the second period, output is $x_{inc}^{K,NE}(t_2^{K,NE})$, which is socially optimal since fee $t_2^{K,NE}$ solves $x_{inc}^{K,NE}(t_2) = q_{SO}^K$, which holds with and without regulator since entry does not ensue in the pooling equilibrium. Therefore, the presence of the regulator ameliorates the environmental externality in the first period, and fully corrects inefficiencies in the second period, ultimately implying that his presence entails a welfare improvement. ■

References

[1] Bagwell, K., and G. Ramey (1991) "Oligopoly limit pricing," The RAND Journal of Economics 22, pp. 155-172.

[2] Cho, I. and D. Kreps (1987) "Signaling games and stable equilibrium," Quarterly Journal of Economics 102, 179-222.

[3] Denicolò, V. (2008) "A signaling model of environmental overcompliance," Journal of Economic Behavior and Organization 68, pp. 293–303.

[4] Espinola-Arredondo, A. and F. Munoz-Garcia (2013) "When does Environmental Regulation Facilitate Entry-Deterring Practices?" Journal of Environmental Economics and Management 65(1), pp. 133-152.

[5] Espinola-Arredondo, A, F. Munoz-Garcia, and J. Bayham (2014) "The Entry-Deterring Effects of Inflexible Regulation," Canadian Journal of Economics, 47(1), pp. 298-324.

[6] Farrell, J. (1987) "Information and the Coase theorem," The Journal of Economic Perspectives 1(2), pp. 113–129.

[7] Greenpeace Report (2009) "HFCs: A growing threat to the climate" Report 58801, December.

[8] Harrington, J.E. Jr. (1986) "Limit pricing when the potential entrant is uncertain of its cost function," Econometrica 54, pp. 429-437.

[9] Harrington, J.E. Jr. (1987) "Oligopolistic entry deterrence under incomplete information," RAND Journal of Economics, 18(2), pp. 211-231.

[10] Lewis, T. R. (1996) "Protecting the environment when costs and benefits are privately known," The RAND Journal of Economics 27, pp. 819-847.

[11] Maxwell, J. and F. Briscoe (1997) "There's Money in the Air: The CFC Ban and DuPont's Regulatory Strategy", Business Strategy and the Environment, vol. 6, pp. 276-286.

[12] Milgrom, P., and J. Roberts (1982) "Predation, reputation, and entry deterrence," Journal of Economic Theory 27, pp. 280-312.

[13] Milgrom, P., and J. Roberts (1986) "Price and advertising signals of product quality," Journal of Political Economy 94, pp. 796-821.

[14] Naess, E. and T. Smith (2009) "Environmentally related taxes in Norway" Statistics Norway/Division for Environmental Statistics. Report 2009/5.

[15] Ridley, David B. (2008) "Herding versus Hotelling: Market entry with costly information," Journal of Economics and Management Strategy 17(3), pp. 607-631.

[16] Roberts, M. J., and M. Spence (1976) "Effluent charges and licenses under uncertainty," Journal of Public Economics 5, pp. 193-208.

[17] Schoonbeek, L., and F. P. Vries. (2009). "Environmental Taxes and Industry Monopolization." Journal of Regulatory Economics 36, pp. 94-106.

[18] Schultz, C. (1999) "Limit Pricing when Incumbents have Conflicting Interests," International Journal of Industrial Organization 17, pp. 801-25.

[19] Segerson, K (1988) "Uncertainty and incentives for nonpoint pollution control," Journal of Environmental Economics and Management 15, pp. 87-98.

[20] Stavins, R.N. (1996) "Correlated uncertainty and policy instrument choice," Journal of Environmental Economics and Management 30(2), pp. 218–232.

[21] Thomas, A. (1995) "Regulating Pollution under Asymmetric Information: The Case of Industrial Wastewater Treatment," Journal of Environmental Economics and Management 28(3), pp. 357–73.

[22] Weitzman, M (1974) "Prices vs. quantities," The Review of Economic Studies 41, pp. 477-491.

[23] Xepapadeas, A.P. (1991) "Environmental policy under imperfect information: Incentives and moral hazard," Journal of Environmental Economics and Management 20, pp. 113-126.