The Entry-Deterring Effects of Inflexible Regulation*

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Abstract

This paper investigates the signaling role of tax policy in promoting, or hindering, the ability of a monopolist to practice entry deterrence. We show that environmental policy can facilitate the incumbent firm's concealment of information from potential entrants, thus deterring entry, and yet entail welfare improvements. Furthermore, we demonstrate that entry deterrence is more likely to arise when environmental regulation cannot be rapidly revised across time if market conditions change (inflexible regimes) than when regulatory agencies can adjust environmental policy over time.

KEYWORDS: Entry deterrence; Signaling; Emission fees; Inflexible Policy.
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1 Introduction

Policy makers may consider the consequences of environmental policy not only on ameliorating pollution, but also on market structure. The existing literature has extensively analyzed the regulators' role in imperfectly competitive markets. However, environmental regulation of industries subject to entry, and characterized by incomplete information, has received less attention. In such a setting, emission fees can facilitate the transmission of information to potential entrants, thus supporting or hindering the incumbent's entry-deterring practices. In this paper, we examine the informative role of environmental regulation when a monopolist incumbent is subject to the threat of entry. Our results provide a better understanding of how regulation may be used to support entry deterrence.

This paper studies an entry-deterrence model with signaling where the incumbent firm is regulated by government agencies that have accumulated information about the incumbent's cost structure over time. Firms that were once publicly owned and managed, but have recently been privatized, represent an example of the information structure that we explore.[1] Alternatively, this information structure applies to firms that face different costs of complying with environmental regulation, as empirically reported by Monty (1991) and Dean and Brown (1995). In particular, an incumbent firm that has operated for several years can assess both its own administrative costs as well as those of the potential entrant, whereas the entrant can only estimate its own costs. The regulator, on the other hand, can easily infer firms' compliance costs, since polluters must recurrently interact with him in order to fulfill the requirements imposed by the environmental policy.

Information about the incumbent's cost structure is, therefore, conveyed or concealed from the entrant depending on both regulation and output; rather than through output alone, as in standard entry-deterrence models where firms operate in the absence of regulation. This introduces a new role for emission fees, since they can be used as antitrust (or trust-promoting) policy. In this paper, we specifically focus on emission fees that cannot be rapidly adjusted over time even if the market structure changes. We refer to this rigid structure as inflexible policy. This type of regulation is commonly observed in settings where environmental policy remains constant across time. For instance, the design of timber yield taxes in California has been unaffected since 1976. Similarly, the electricity tax in Spain was not modified during 1998-2003, and the tax on aviation noise pollution in France has remained constant since 2003.[2]

As a benchmark for comparison, we first analyze equilibrium behavior under complete information. In this context, regulation is socially optimal when entry does not ensue; whereas it entails inefficiencies when entry occurs (second-best policy), since the regulator is unable to adjust emission

[1] Several public companies were privatized in the United Kingdom, such as British Steel (privatized in 1988), Enterprise Oil (1984), British Energy (1996) and British Coal (1994). Other examples include LUKOil (1995) and Novolipetsk Steel (1995) in Russia, New Zealand Steel company (1987), and Nova Scotia Power (1992) and PetroCanada (1991) in Canada.

[2] These laws establish a baseline fee, and allow for automatic adjustments based on inflation, property taxation, etc. However, no amendments have been introduced that modify the baseline fee. For more details, see California State Board of Equalization's website, the Spanish Internal Revenue Service (AEAT, Report for 2008, chapter 6), and the French Civil Aviation Authority (Environmental Report for 2008), respectively.

fees across time. Under incomplete information, we identify the existence of an informative equilibrium, in which the incumbent's cost efficiency is fully revealed to the entrant, and an uninformative equilibrium, where information is successfully concealed.

In the informative equilibrium, the efficient incumbent overproduces in order to signal its type, thus deterring entry, which generates larger pollution levels than under complete information.[3] In this setting, the regulator sets more stringent emission fees in order to correct such an externality. However, this stringent regulation remains unaltered in the second period, giving rise to an additional form of inefficiency, absent under complete information. While social welfare in the informative equilibrium is lower than under complete information, we show that the presence of the regulator is still welfare improving in incomplete information contexts. In particular, environmental regulation, despite not inducing socially optimal outcomes, helps ameliorate the increase in pollution associated with the incumbent's overproduction effort, thus entailing a welfare improvement.

In the case of an uninformative equilibrium, the inefficient incumbent mimics the efficient firm in order to conceal its type, and thus deters entry. In this context, the regulator faces a trade-off between two alternatives: either set a stringent emission fee that helps the incumbent successfully avoid entry; or choose a fee that reveals the incumbent's type. The more stringent fee causes an inefficient production, but entails savings in entry costs by deterring entry. We show that the regulator sets stringent fees, which deter entry, when entry costs are sufficiently high.

In addition, we demonstrate that entry-deterring practices emerge under larger conditions when environmental policy is inflexible as opposed to flexible policy, which can be rapidly redesigned over time.[4] Unlike inflexible policies, the emission fee that conveys information to potential entrants in a flexible regime yields socially optimal output levels. Hence, the regulator is less attracted to facilitate the incumbent's entry-deterring practices under a flexible policy regime.

From a policy perspective, our results suggest that regulators should promote more responsive environmental agencies, which are able to rapidly adjust emission fees once market conditions change, since they may prevent domestic monopolists from practicing entry deterrence. Conversely, inflexible policies become more appropriate if the regulator aims at promoting the monopolistic position of local firms, since these policies expand the conditions under which entry can be successfully deterred. Therefore, our findings identify a benefit of modern environmental protection agencies often overlooked by the environmental regulation literature. Agencies that rapidly redesign their policies to market conditions can hinder entry-deterring practices. Finally, note that our analysis of strategic regulatory agencies is not confined to environmental economics, but can be extended

[3] This strategy profile can explain the entry-deterring practices of the chemical company Dow, during the 1970s. Dow, a near monopolist in the U.S. magnesium industry during the 1960-80, was subject to the EPA regulation of carbon monoxide and particulate matter. In particular, these two pollutants are generated in the production of magnesium, and they were included in the Clean Air Act Extension of 1970, as part of the National Ambient Air Quality Standards. Facing the threat of entry by several competitors, Dow significantly increased its magnesium production during the early 1970s and, as a consequence, successfully deterred the entry of Kaiser Aluminum, Harvey Aluminum, and Norsk Hydro, among others; and delayed the entry of Alcoa and National Lead for several years. For more details, see Lieberman (1987).

[4] Flexible policy regimes, and their entry-deterring implications, have been analyzed by Espinola-Arredondo and Munoz-Garcia (2012)

to settings in which public goods are promoted through subsidies, or to the field of international trade, where tariff policy and output serve as signals to uninformed foreign firms seeking to sell their products in the domestic market.

Related literature. Since the seminal work of Milgrom and Roberts (1982), several studies have examined firms' overproduction as a tool to deter entry; see Harrington (1986), Bagwell and Ramey (1991) and Riley (2008). Nonetheless, these papers abstract from the regulatory context in which firms operate. In contrast, our model considers the role of regulation in entry-deterrence settings and examines its effects on information transmission. Milgrom and Roberts (1986) analyze a model of entry deterrence where the informed firm uses two signals, price and advertising, to convey the quality of her product to consumers. They show that the introduction of an additional signal reduces the extent of the firm's separating effort.[5] Similarly, we study how two different signals —emission fees and output level— convey information to the potential entrant. In our model, signals stem from two different informed agents: the regulator and the incumbent. In contrast to Milgrom and Roberts (1986), we demonstrate that the presence of two informed agents can not only facilitate the transmission of information to the potential entrant, but also hinder such communication in certain contexts. Bagwell and Ramey (1991) examine a limit-pricing game where two incumbent duopolists signal their common cost structure to an uninformed entrant. They show that no pooling equilibrium can be sustained in which two inefficient incumbents competing in prices overproduce in order to signal their type. Our model, by contrast, considers settings where the regulator and incumbent may be willing to conceal information from the entrant.

In the area of environmental policy under incomplete information, several authors have analyzed optimal policies when the regulator is uninformed about the incumbent's type; see, among others, Weitzman (1974), Roberts and Spence (1976), Segerson (1988), Xepapadeas (1991), Lewis (1996) and Segerson and Wu (2006). Nonetheless, these studies do not consider the signaling role of environmental policy. In contrast, Antelo and Loureiro (2009) examine a regulator who can infer the incumbent's costs upon observing her first-period output. Our model, however, differs along several dimensions. First, we consider situations where the regulator has accumulated information about the incumbent's costs over time, which allows for emission fees to play a signaling role.[6] Second, our paper provides a comparison of flexible and inflexible policies under signaling contexts.[7] Lastly, our results analyze both separating and pooling equilibria (informative and uninformative

[5] Bagwell and Ramey (1990) and Albaek and Overgaard (1994) also examine entry deterrence in a model where the potential entrant can perfectly observe both the incumbent's pre-entry pricing strategy and its advertising expenditures.

[6] Barigozzi and Villeneuve (2006) also consider the signaling role of tax policy. However, they do not study an entry deterrence model. In particular, their model analyzes a regulator who is informed about the health benefits of a particular product while potential consumers use tax policy to form beliefs about such quality.

[7] Ko et al. (1992) also compare flexible and inflexible environmental policies under a complete information context where a single incumbent produces stock externalities, i.e., pollution that does not fully dissipate across periods, without allowing for potential entry. Because entry cannot occur in their setting, the optimal policy path across periods mainly depends on the dissipation rate. In our model, in contrast, pollution fully dissipates across periods but entry may occur, thus affecting the social planner's optimal policy path under a flexible and inflexible policy regime.

equilibria, respectively) and focus on those equilibria surviving standard equilibrium refinements.

The next section describes the model under complete information. Section 3 examines the signaling game, while section 4 (5) describes the informative (uninformative, respectively) equilibrium, and compares equilibrium welfare levels to two benchmarks: complete information settings and entry-deterrence models in which the regulator is absent. Section 6 then examines whether the uninformative equilibrium, and its entry-deterring outcome, can be sustained under larger conditions when policy regimes are flexible or inflexible, also providing a discussion for policy implications. Section 7 concludes.

2 Complete information

Consider an entry game with a monopolist incumbent, an entrant who decides whether or not to join the market, and a regulator who sets an emission fee per unit of output. We first examine the case where all players are informed about the incumbent's marginal cost, and then the case in which only the entrant is uninformed. We study a two-stage game where, in the first stage, the regulator chooses a pollution tax and the incumbent chooses output; and in the second stage, the potential entrant decides whether or not to enter, and the firm(s) in the market select(s) output. The regulator's social welfare function considers consumer and producer surplus, the tax revenue arising from emission fees, and the environmental damage from pollution, defined as $ED \equiv d \times X^2$, where X denotes aggregate output. Upon observing a pollution tax t, the incumbent monopolist maximizes profits by solving

$$\max_{q \geq 0} \ (1-q)q - \left(c_{inc}^K + t\right) q$$

where $K = \{H, L\}$ denotes the incumbent's type, and $P(q) = 1 - q$ represents the inverse demand function. The incumbent's constant marginal costs are either high H or low L, i.e., $1 > c_{inc}^H > c_{inc}^L \geq 0$, where subscript inc denotes the incumbent. In the second stage, the potential entrant decides whether or not to join. If entry does not ensue, the incumbent maintains its monopoly power, while if entry occurs, firms compete as Cournot duopolists, simultaneously selecting production levels x_{inc} and x_{ent}, for the incumbent and entrant, respectively.

We consider that the entrant's marginal cost, c_{ent}, coincides with that of the high-cost incumbent. Intuitively, newcomers lack experience in the industry; or alternatively, they still ignore some of the administrative details of complying with the environmental regulation. The incumbent, however, can have either benefited from a significant experience in the industry, which lowered its production costs, from c_{inc}^H to c_{inc}^L, or such experience might have not entailed cost savings relative to the entrant, i.e., $c_{inc}^H = c_{ent}$. 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.

No entry. In the case of no entry, the regulator seeks to induce the same socially optimal output q_{SO}^K in both periods. This output level is illustrated in the horizontal axis of figure 1a, as the production for which social marginal benefits and damages coincide, i.e., $q_{SO}^K = \frac{1-c_{inc}^K}{1+2d}$ solves $MB^{K,NE}(q) = MD^{NE}(q)$. The figure also depicts the emission fee that induces the monopolist to produce at an efficient output level, i.e., $t^{K,NE} = MP_{inc}^{K,NE}(q_{SO}^K)$, where $MP_{inc}^{K,NE}(q)$ denotes the incumbent's marginal profits. (Alternatively, the monopolist sets output function $q^K(t) = \frac{1-c_{inc}^K-t}{2}$ for any emission fee t. Anticipating such an output function, the regulator sets the level of $t^{K,NE}$ that solves $q^K(t) = q_{SO}^K$.) In particular, such socially optimal fee is $t^{K,NE} = (2d-1)\frac{1-c_{inc}^K}{1+2d}$. Therefore, if entry does not ensue, the regulator induces the socially optimal output in both periods, and no inefficiencies arise during any stage of the game.[8]

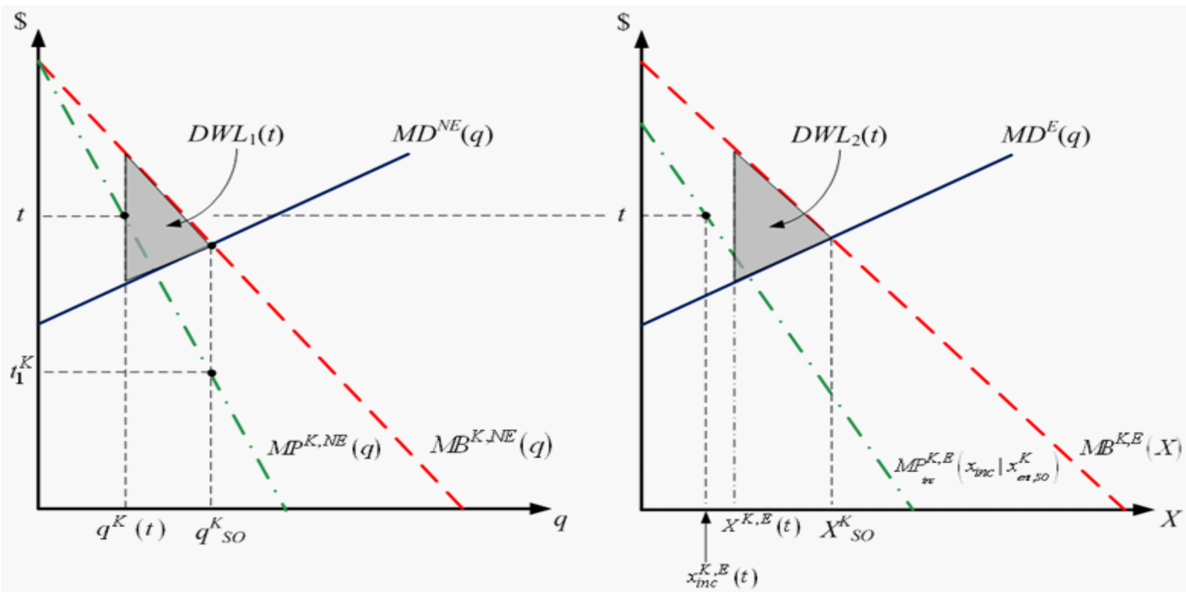

Fig. 1a: First-period DWL

Fig. 1b: Second-period DWL

Entry. If entry occurs, however, the regulator would need to set different emission fees to the first-period monopolist than to the second-period duopolists in order to implement the socially optimal output; in particular, fees under duopoly would need to be more stringent, as shown by Buchanan (1969). Hence, a fee that remains constant in both market structures generates a deadweight loss in one or both periods. Figure 1a represents the first-period welfare loss that arises from an inflexible fee t above the socially optimal fee $t^{K,NE}$. In particular, fee t leads to a monopoly output $q^K(t)$ below the socially optimal output q_{SO}^K, yielding a deadweight loss of

$$DWL_1(t) \equiv \int_{q^K(t)}^{q_{SO}^K} \left[MB^{K,NE}(q) - MD^{NE}(q)\right] dq,$$

where output $q^K(t)$ solves $MP_{inc}^{K,NE}(q) = t$, i.e., $q^K(t)$ is the monopoly profit-maximizing output for a given fee t. Similarly, the deadweight loss associated to inflexible fee t in the second period is

[8] Note that fee $t^{K,NE}$ is, hence, increasing in d, and increasing in c_{inc}^K. In addition, when $d \leq 0.5$, emission fee $t^{K,NE}$ collapses to zero. Since we analyze the effect of taxes on output and welfare, we hereafter focus on settings where the environmental damage satisfies $d > 0.5$ and, therefore, emission fees are positive.

given by

$$DWL_2(t) \equiv \int_{X^{K,E}(t)}^{X_{SO}^{K}} \left[MB^{K,E}(X) - MD^{E}(X)\right] dX,$$

where $X^{K,E}(t) = x_{inc}^{K,E}(t) + x_{ent}^{K,E}(t)$ and output $x_j^{K,E}(t)$ solves $MP_j^{K,E}\left(x_j | x_{k,SO}^{K,E}\right) = t$ for all firm j, i.e., $x_j^{K,E}(t)$ represents firm j's profit-maximizing output for a given fee t after entry. Deadweight loss $DWL_2(t)$ is depicted in figure 1b. Hence, the regulator minimizes the discounted sum of the absolute value of deadweight losses across both periods, choosing a fee t that solves

$$\min_{t} \ |DWL_1(t)| + \delta\, |DWL_2(t)| \tag{1}$$

where $\delta \in [0, 1]$ denotes the discount factor.[9] The following lemma describes emission fees in the subgame perfect equilibrium of the game.

Lemma 1 (Complete information). *When the incumbent's costs are low, entry does not ensue (NE), and the regulator selects an emission fee* $t^{L,NE} = (2d-1)\frac{1-c_{inc}^{L}}{1+2d}$. *The incumbent responds with output function* $q^{L}(t) = \frac{1-c_{inc}^{L}-t}{2}$, *entailing a socially optimal output* $q^{L}(t^{L,NE}) = \frac{1-c_{inc}^{L}}{1+2d} \equiv q_{SO}^{L}$ *during both periods. When the incumbent's costs are high, entry ensues (E), and the regulator chooses a fee* $t^{H,E}$, *where* $t^{H,E}$ *solves (1). The incumbent responds with a first-period output function* $q^{H}(t) = \frac{1-c_{inc}^{H}-t}{2}$ *and firms produce according to* $x_i^{H,E}(t) = \frac{1-c_i^{H}-t}{3}$ *where* $i = \{inc, ent\}$ *and* $j \neq i$ *in the second period. Emission fees, and the resulting output levels for both firms, are positive as long as firms' costs are not extremely different, i.e.,* $c_{inc}^{L} < c_{inc}^{H} < \frac{1+2dc_{inc}^{L}}{1+2d}$.

Intuitively, if the regulator had the ability to redesign environmental policy across periods, he would set a less stringent fee to the first-period monopoly but a more stringent fee to the second-period duopolists. However, since in our model he is unable to adjust emission fees across time, he sets a fee $t^{H,E}$ that minimizes the deadweight loss arising from the inefficiencies created by a constant fee in both periods. In particular, $t^{H,E}$ becomes a weighted average of the first- and second-period fees that the regulator would set if he had the ability to redesign environmental policy across periods. For instance, when $\delta = 1$, fee $t^{H,E}$ assigns a weight of $\frac{9}{25}$ to the first-period optimal fee under monopoly, and $\frac{16}{25}$ to the second-period optimal fee under duopoly.[10] (For more details, see the proof of Lemma 1).

3 Incomplete information

We now assume the entrant is unable to observe the extent to which the incumbent's costs have decreased as a result of its accumulated experience complying with the environmental policy. As a

[9] In order to allow for the case in which $t \geq t^{K,NE}$ (as depicted in figure 1a), and that in which $t < t^{K,NE}$, expression (1) considers the absolute value of the deadweight loss of fee t.

[10] When the discount factor approaches zero, the weight on the first-period optimal fee becomes one, thus generating no first-period inefficiencies.

consequence, the entrant must base his entry decision on the observed first-period output and the (constant) emission fee. The time structure of this signaling game is as follows.

1. Nature decides the realization of the incumbent's marginal costs, either high or low, with probabilities $p \in (0,1)$ and $1-p$, respectively. Incumbent and regulator privately observe this realization but the entrant does not.

2. The regulator imposes an environmental tax t on the incumbent's output and the incumbent responds choosing her first-period output level, $q(t)$.

3. Observing tax t and the incumbent's output level $q(t)$, the entrant forms beliefs about the incumbent's marginal costs. Let $\mu(c^H_{inc}|q(t),t)$ denote the entrant's posterior belief that the incumbent's costs are high.

4. Given these beliefs, the entrant decides whether or not to enter the industry.

   (a) If entry does not occur, the incumbent responds by producing a monopoly output $x^{K,NE}_{inc}(t)$.

   (b) If, in contrast, entry ensues, the entrant observes the incumbent's costs and both firms then compete as Cournot duopolists, producing $x^{K,E}_{inc}(t)$ and $x^{K,E}_{ent}(t)$.

For compactness, let $D^K_{ent}(t)$ denote the entrant's duopoly profits in equilibrium under a given tax t when the entrant faces a K-type incumbent. To make the entry decision interesting, consider that when the incumbent's costs are low, entry is unprofitable for any emission fee t, i.e., $D^L_{ent}(t) < F$ for all t. Hence, the entrant stays out even when emission fees are absent, i.e., $D^L_{ent}(0) < F$; as in standard entry-deterrence games where the regulator is absent. By contrast, when the incumbent's costs are high, entry is profitable as long as emission fees are not extremely high.[11] Let us briefly describe the incentive compatibility conditions for the high- and low-cost incumbent (for a detailed explanation of these conditions, see proof of Proposition 1 in the appendix). The high-cost incumbent selects a complete information profit-maximizing output, $q^H(t)$, for any tax t. She chooses $q^H(t)$ rather than deviating towards $q^A(t)$, where $q^A(t)$ exceeds the low-cost incumbent's first-period output under complete information, $q^L(t)$, if

$$M^H_{inc}(q^H(t),t) + \delta D^H_{inc}(t) \geq M^H_{inc}(q^A(t),t) + \delta \overline{M}^H_{inc}(t), \tag{C1}$$

where $\delta \in [0,1]$ represents the firm's discount factor, $M^H_{inc}(q(t),t)$ denotes the incumbent's first-period monopoly profits for any output function $q(t)$ and fee t, $D^H_{inc}(t) \equiv \frac{(1-c^H_{inc}-t)^2}{9}$ is the incumbent's duopoly profits and $\overline{M}^H_{inc}(t) \equiv \frac{(1-c^H_{inc}-t)^2}{4}$ represents her second-period monopoly profits.

[11] That is, profit function $D^H_{ent}(t) = \frac{(1-c^H_{inc}-t)^2}{9}$ originates above F, but falls below it for all $t \geq \bar{t}$, where $\bar{t}$ solves $D^H_{ent}(t) = F$, i.e., $\bar{t} = 1-c^H_{inc}-3\sqrt{F}$. Such emission fee would, however, blockade entry, thus nullifying the informative role of first-period actions. Since we focus on emission fees that conveys information to the uninformed entrant, we focus on fees below $\bar{t}$. (In addition, it is straightforward to show that all emission fees in our equilibrium results lie below $\bar{t}$).

The low-cost incumbent chooses $q^A(t)$ over $q^L(t)$ if

$$M^L_{inc}(q^A(t),t) + \delta\overline{M}^L_{inc}(t) \geq M^L_{inc}(q^L(t),t) + \delta D^L_{inc}(t). \tag{C2}$$

Thus, conditions C1-C2 guarantee that the high-cost incumbent does not have incentives to mimic $q^A(t)$. The following section focuses on strategy profiles where information about the incumbent's costs is conveyed to the entrant (referred as "informative" equilibria), and afterwards we analyze those profiles where the entrant cannot infer the incumbent's type after observing the regulator's and incumbent's choices (i.e., "uninformative" equilibria).

4 Informative equilibrium

The entrant can infer accurate information about the incumbent's type when at least one of the privately informed agents, the incumbent or the regulator, selects a type-dependent strategy.[12] Specifically, this occurs when either: (1) the regulator chooses a type-dependent tax level and both types of firm use the same output function; or (2) the regulator sets a type-independent tax level while the incumbent selects a type-dependent output function; or (3) both informed agents select a type-dependent first-period action.[13] However, the following proposition demonstrates that only the third type of informative equilibrium can be supported as a Perfect Bayesian Equilibrium (PBE). We also show that only the equilibrium implying the smallest deviation from agents' behavior under complete information, i.e., the least-costly separating PBE, survives the Cho and Kreps' (1987) Intuitive Criterion. (For compactness, Proposition 1 does not specify the entrant's beliefs after observing each of the possible pairs of emission fees and output levels. We provide an intuitive explanation of these beliefs at the end of this section; for more details, see proof of Proposition 1 in the appendix.)

Proposition 1. *An informative equilibrium can be sustained when priors satisfy* $p > \overline{p}\left(t^{L,NE}\right) \equiv \frac{F-D^L_{ent}\left(t^{L,NE}\right)}{D^H_{ent}(t^{L,NE})-D^L_{ent}(t^{L,NE})}$, *in which the regulator selects type-dependent emission fees* $(t^{H,E}, t^A)$, *and the incumbent responds choosing output function* $q^H(t) = \frac{1-c^H_{inc}-t}{2}$ *when her costs are high and* $q^A(t) = \frac{(1-c^H_{inc}-t)(3+\sqrt{5}\sqrt{\delta})}{6}$ *when her costs are low, where* $q^A(t)$ *solves condition C1 with equality, if and only if the entrant's costs are sufficiently low, i.e.,* $c_{ent} < \beta \equiv \frac{(3\sqrt{5}-5)(1-c^L_{inc})+2(1+2d)c^L_{inc}}{2(1+2d)}$, *where* $\delta = 1$. *Finally, emission fee* t^A *solves*

$$\min_{t} \;\; |DWL_1(t)| + \delta\,|DWL_2(t)|$$

[12] In a slight abuse of notation, we hereafter use "type-dependent tax" to denote the regulator's strategy when he selects an emission fee conditional on the incumbent's type, and "type-independent tax" when such fee is unconditional on the incumbent's type.

[13] Note that in all cases the output level ultimately observed by the potential entrant differs between the high- and low-cost incumbent, which allows the entrant to infer the incumbent's production cost.

where the first-period deadweight loss is $DWL_1(t) \equiv \int_{q^A(t)}^{q^L_{SO}} \left[MB^{L,NE}(q) - MD^{NE}(q)\right] dq$*; whereas that in the second-period is* $DWL_2(t) \equiv \int_{x^{L,NE}_{inc}(t)}^{x^L_{SO}} \left[MB^{L,NE}(x) - MD^{NE}(x)\right] dx$.

The low-cost incumbent selects an output function $q^A(t)$ above that under complete information, $q^L(t)$, in order to reveal her type to the entrant, and thus deter entry. If the regulator had the ability to redesign emission fees across time, such higher production schedule would call for more stringent fees during the first period (in order to compensate for the increase in pollution arising from the incumbent's separating effort), but less stringent fees in the second period, once the incumbent has deterred entry and produces her monopoly output. However, the regulator cannot adjust environmental policy across periods in order to precisely induce the social optimum. Hence, setting a constant fee across time produces inefficiencies in either one or both periods and, as under complete information, the regulator must select an emission fee that minimizes the deadweight loss resulting from such inflexible fee.[14] Furthermore, the low-cost incumbent finds it profitable to exert a "separating effort," if the potential entrant is relatively efficient, i.e., $c_{ent} < \beta$, and, hence, the incumbent anticipates a "tough" competition in the post-entry game.

Consistent signals: This informative equilibrium can be sustained if the entrant observes "consistent" signals from both informed players. That is, after observing an equilibrium fee t^A, the entrant confirms that the incumbent's type must be low if, in addition, he observes an output level $q^A(t^A)$. If, instead, the output does not coincide with $q^A(t^A)$, the information conveyed in emission fee t^A is "inconsistent" with the output choice, and the entrant believes that the incumbent's costs must be high, inducing entry. Likewise, a high-cost incumbent facing $t^{H,E}$ cannot deter entry by deviating to an output function $q(t^{H,E}) \neq q^H(t^{H,E})$.[15]

The consistency requirement on both signals explains why strategy profiles where only one agent, either the regulator or the incumbent, chooses a type-dependent strategy cannot be sustained as equilibria of the signaling game. Intuitively, if the regulator chooses a type-dependent tax level and both types of incumbent use the same output function, the output level that the entrant ultimately observes differs between the high- and low-cost incumbent, thus allowing the entrant to infer the incumbent's type. However, in such strategy profile the high-cost incumbent would attract entry and, conditional on entry, this firm obtains a larger profit deviating to the type-dependent output function $q^H(t)$, as described in our result of Proposition 1.[16]

[14] For instance, for parameter values $\delta = 1$, $c^H_{inc} = 1/4$ and $c^L_{inc} = 0$, emission fee t^A becomes $t^A = \frac{39+9\sqrt{5}-\frac{12(6+\sqrt{5})}{(1+2d)}}{2(23+6\sqrt{5})}$.

[15] As shown in the proof of Proposition 1, these beliefs are consistent with Cho and Kreps' (1987) Intuitive Criterion.

[16] A similar argument applies to strategy profiles where, instead, the regulator sets a type-independent tax level, $t' \neq t^{H,E}$, while the incumbent selects a type-dependent output function. In this context, the entrant can also deduce the incumbent's type upon observing fee $t' \neq t^{H,E}$ and output level $q^H(t')$, and join the market. However, conditional on entry, the regulator facing a high-cost incumbent can increase social welfare by deviating to the type-dependent fee $t^{H,E}$.

4.1 Welfare properties of the informative equilibrium

In this subsection we examine the welfare that arises in the informative equilibrium, $W_{IE}^{L,R}$, where superscript R denotes the presence of the regulator, and compare it with that emerging under complete information, $W_{CI}^{L,R}$.[17] For completeness, we also contrast social welfare with and without regulator, i.e., $W_{IE}^{L,R}$ and $W_{IE}^{L,NR}$, where NR represents the absence of regulation, thus providing a measure of the welfare benefits of regulation in incomplete information settings.

Corollary 1. *Social welfare in the informative equilibrium is lower than under complete information, for all parameter values, i.e.,* $W_{IE}^{L,R} < W_{CI}^{L,R}$*. However, social welfare in the informative equilibrium is larger with than without regulation, i.e.,* $W_{IE}^{L,R} > W_{IE}^{L,NR}$*.*

Under complete information, the entrant does not join the market when the incumbent's costs are low, and the latter produces according to monopoly output function $q^L(t)$ in both periods. In this setting, the regulator can hence induce the socially optimal output by setting fee $t^{L,NE}$, and no inefficiencies arise. In contrast, under the informative equilibrium, inefficiencies emerge in both periods: (1) overproduction arises during the first period, since output level $q^A(t^A)$ exceeds that under complete information, $q^L(t^{L,NE})$; and (2) underproduction emerges in the second period. In particular, the informative equilibrium fee t^A is more stringent than the complete information fee, $t^{L,NE}$. Furthermore, the incumbent produces according to her monopoly output function, $x_{inc}^{L,NE}(t)$, and the stringent fee t^A yields an output level below the social optimum, i.e., $x_{inc}^{L,NE}(t^A) < x_{inc}^{L,NE}(t^{L,NE})$. As a consequence, inefficiencies arise in both periods relative to complete information, and welfare satisfies $W_{IE}^{L,R} < W_{CI}^{L,R}$.

While social welfare in the informative equilibrium is lower than under complete information, the presence of the regulator is still beneficial in incomplete information contexts. Specifically, in the informative equilibrium that emerges in standard entry-deterrence games without a regulator, as in Milgrom and Roberts (1982), the incumbent increases its output (and pollution), relative to complete information, in order to signal her type to potential entrants. Thus, an additional form of inefficiency emerges under incomplete information which did not exist under complete information. Hence, the introduction of regulation, despite not inducing socially optimal levels of pollution in either period, ameliorates such overproduction (approaching output levels to the social optimum), ultimately generating a larger welfare, i.e., $W_{IE}^{L,R} > W_{IE}^{L,NR}$.

Finally, note that our results differ from those in flexible policy regimes, whereby the regulator can adjust environmental policy across time; as identified in Espinola-Arredondo and Munoz-Garcia (2012). In particular, they show that, by varying emission fees, the regulator can induce a socially optimal output during both periods. Since a flexible regime promotes optimal outcomes, the welfare benefits of introducing regulation in incomplete information settings are substantial. In contrast, the welfare benefits of inflexible regulation are smaller, since the presence of the regulator cannot guarantee optimal output levels in both periods.

[17] Since the high-cost incumbent's behavior coincides in the informative equilibrium and the complete information context, thus entailing the same associated welfare, we focus on the low-cost incumbent.

5 Uninformative equilibrium

In this section, we examine the case where both regulator and incumbent choose a type-independent strategy, and therefore no information is conveyed to the entrant.[18]

Proposition 2. *An uninformative equilibrium can be sustained when priors satisfy* $p \leq \overline{p}\left(t^{L,NE}\right)$ *in which the regulator selects a type-independent emission fee* $t^{L,NE}$*, and both types of incumbent respond choosing output function* $q^{L}(t)$*, when entry costs are sufficiently large, i.e.,* $F > F^{Inflex}(d)$*, where*

$$F^{Inflex}(d) \equiv \frac{\left[121 + 100(d-1)d\right]\left(c_{inc}^{H}\right)^{2} + 25B\left(c_{inc}^{L}\right)^{2} + c_{inc}^{H}\left[8 - 50Bc_{inc}^{L}\right] - 4}{200(1+2d)}$$

and $B \equiv 5 + 4(d-1)d$.

In order to mimic the low-cost incumbent, the high-cost firm selects output function $q^{L}(t)$. Since, in addition, the regulator chooses a type-independent emission fee $t^{L,NE}$, the entrant cannot infer the incumbent's type and stays out of the industry given his low priors. Hence, both the high-cost incumbent and the regulator sacrifice a portion of their first-period profits and social welfare, respectively, in order to conceal the incumbent's type and protect the market from entry. Specifically, the regulator sets a tax $t^{L,NE}$ different from that under complete information, $t^{H,E}$, thus exacerbating the inefficiencies that emerge in the complete information setting depicted in figure 1.[19] Nonetheless, tax $t^{L,NE}$ yields a second-period welfare gain since, relative to complete information, entry is deterred in the uninformative equilibrium, thus entailing savings in the fixed entry cost F. When this second-period welfare gain outweighs the welfare loss from overtaxation, overall welfare increases, which occurs when entry costs are sufficiently high, i.e., $F > F^{Inflex}(d)$.

Intuitively, this suggests that in the uninformative equilibrium both informed agents must share the burden of concealing information from the entrant in order to deter entry. Since in this context both the regulator and the incumbent prefer no entry, this case illustrates settings where their preferences are "aligned." In contrast, when the social costs of over-taxation are high, the regulator prefers entry while the incumbent does not, i.e., preferences are "misaligned." Our results imply that when preferences are misaligned only the informative equilibrium can be sustained. In this case, the regulator manages to reveal accurate information to the entrant, as described in Proposition 1. However, if their preferences are aligned, either the informative or uninformative equilibrium can be supported, depending on the prior p.

[18] Since we analyze social welfare across only two time periods, we hereafter assume, for simplicity, no discounting of future payoffs.

[19] In particular, it is straightforward to show that $t^{L,NE} > t^{H,E}$ if and only if costs satisfy $\frac{8+25(2d-1)c_{inc}^{L}}{8+25(2d-1)} < c_{inc}^{H} < \frac{1+2dc_{inc}^{L}}{1+2d}$. Hence, overtaxation arises when costs are relatively high, but undertaxation emerges when they are relatively low, i.e., $c_{inc}^{H} < \frac{8+25(2d-1)c_{inc}^{L}}{8+25(2d-1)}$. Nonetheless, in both settings an inefficient tax level is implemented, thus generating welfare losses relative to complete information.

5.1 Welfare properties of the uninformative equilibrium

The following corollary evaluates the welfare arising under the uninformative equilibrium, $W_{UE}^{L,R}$, and compares it with that in complete information settings, $W_{CI}^{H,R}$.[20] Similar to section 4.1, we examine social welfare with and without regulation, $W_{UE}^{H,R}$ and $W_{UE}^{H,NR}$, in order to analyze the welfare benefits of environmental regulation.

Corollary 2. *Social welfare in the uninformative equilibrium is larger than under complete information, for all parameter values, i.e.,* $W_{UE}^{H,R} > W_{CI}^{H,R}$. *In addition, social welfare in the uninformative equilibrium is larger when the regulator is present than when he is absent, i.e.,* $W_{UE}^{H,R} > W_{UE}^{H,NR}$.

As described in Proposition 2, production is not socially optimal under both the uninformative equilibrium and the complete information setting. Nonetheless, the regulator is only willing to set the fee $t^{L,NE}$ when the larger inefficiencies that such fee entails, relative to the complete-information fee $t^{H,E}$, are offset by the savings in the entry costs F. Thus, the social welfare that arises in the entry-deterring equilibrium, $W_{UE}^{H,R}$, exceeds that from attracting the entrant to the industry, $W_{CI}^{H,R}$.

Regarding the welfare benefits of introducing environmental regulation, a similar argument applies. Under incomplete information, standard entry deterrence games in which regulation is absent prescribe that the high-cost incumbent overproduces in order to conceal her type from potential competitors. Such overproduction generates more pollution than under complete information, i.e., $W_{UE}^{H,NR}$ is low. Hence, the presence of the regulator, under incomplete information, curbs pollution levels, thus becoming welfare improving.

6 Flexible vs. Inflexible regimes

Let us now compare our equilibrium results with those in flexible policy regimes. Our aim is to evaluate which regime facilitates the emergence of entry-deterring practices under a larger set of parameters. In particular, figure 2 depicts cutoff $F^{Inflex}(d)$ of Proposition 2.[21] Recall that the set of $(F, d)-$pairs above this cutoff indicates parameter combinations for which the uninformative equilibrium can be sustained, i.e., $F > F^{Inflex}(d)$, and thus entry is deterred under an inflexible policy. For comparison, figure 2 also includes cutoff $F^{Flex}(d)$, which represents the set of $(F, d)-$pairs above which the uninformative equilibrium emerges under a flexible policy; as devel-

[20] Since the output function of the low-cost incumbent coincides in both information settings, thus yielding the same social welfare, but that of the high-cost incumbent does not, we restrict our attention to the high-cost incumbent alone.

[21] For simplicity, the figure considers $c_{inc}^{H} = 1/4$ and $c_{inc}^{L} = 0$. Other parameter combinations yield similar results, and can be provided by the authors upon request.

oped by Espinola-Arredondo and Munoz-Garcia (2012).[22]

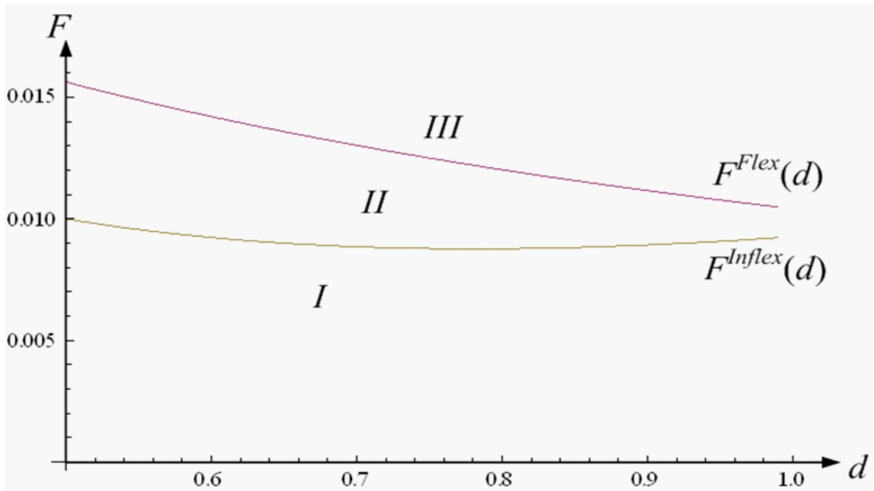

Fig. 2. Entry deterrence under flexible and inflexible regimes.

First, note that $F^{Flex}(d) > F^{Inflex}(d)$. Intuitively, this ranking implies that the range of entry costs, F, for which the regulator promotes entry deterrence in the uninformative equilibrium of the game is smaller under a flexible than an inflexible policy regime. Under a flexible regime, the regulator faces two alternatives: either set an emission fee that facilitates the incumbent's practice of entry deterrence (which generates inefficiencies but entails savings in the entry cost), or choose an emission fee that conveys information to potential entrants, thus attracting them to the industry. Since the latter alternative induces a socially optimal output, the regulator is only willing to select an entry-deterring fee if savings in entry costs are sufficiently high, i.e., $F > F^{Flex}(d)$ in region III. When operating under an inflexible regime, the regulator faces a similar trade-off between saving entry costs and economic efficiency. However, in this regime, entry does not yield optimal outcomes, making entry deterrence relatively more attractive. As a consequence, the regulator is more willing to select entry-deterring fees under an inflexible than a flexible regime, i.e., entry deterrence is sustainable in both regions II and III. Finally, in region I where $F < F^{Inflex}(d)$, the savings from the fixed entry cost are so small that the uninformative equilibrium cannot be sustained, neither under a flexible or inflexible regime. Essentially, the burden from overtaxation associated with this entry-deterring equilibrium would exceed the (minor) savings in entry costs.

6.1 Discussion

Developing more responsive environmental agencies. Our results suggest that the uninformative equilibrium, and thus entry-deterring practices, are more likely to emerge in countries with inflexible policies. We would, hence, expect incumbent firms to lobby for such inflexible regulation. By

[22] In particular, cutoff $F^{Flex}(d) \equiv \frac{\left(c_{inc}^{H}-c_{inc}^{H}\right)^2}{(1+2d)}$ which, for parameters $c_{inc}^{H} = 1/4$ and $c_{inc}^{L} = 0$, becomes $\frac{1}{32+64d}$.

contrast, environmental agencies that rapidly redesign their policies to market conditions would hinder firms' entry-deterring practices. Since inflexible regimes are more likely to arise, for instance, in developing countries who recently started to impose emission fees on local firms but still lack responsive environmental agencies, our findings provide an often overlooked benefit from developing less rigid institutions. In addition, our study suggests that the centralization of environmental regulation —such as requiring that minor adjustments of the policy must be approved by Congress— would reduce its responsiveness to changes in the market structure; thus facilitating entry-deterring practices and hindering competition.

Small, but positive, welfare benefits. We also show that the welfare benefits of inflexible environmental regulation are smaller than those of a flexible policy. Nonetheless, if a country's institutional setting is inflexible, our results suggest that emission fees still generate welfare benefits; both when the affected industries operate in complete and incomplete information contexts.

Convey or conceal information? Finally, our paper identifies a new role of emission fees often overlooked when evaluating environmental policy; namely, its ability to convey or conceal information to potential competitors. In particular, over-taxation helps the incumbent hide her type from potential competitors, thus hindering entry. Such practice, however, does not necessarily entail welfare losses relative to complete information. Indeed, our results demonstrate that the regulator is only willing to practice such concealment strategy when it yields a larger social welfare than under complete information.

7 Conclusions

Our paper investigates the use of tax policy to promote or hinder the ability of a monopolist to practice entry deterrence. While both informative and uninformative equilibria can be sustained — where information is conveyed or concealed from the entrant, respectively— we show that inflexible policies facilitate the incumbent's concealment of information under larger conditions than flexible policies. Therefore, our results identify a potential shortcoming of inflexible policies; namely, facilitating firms' ability to practice entry deterrence.

Different extensions of this model would enhance its predictive power in more realistic settings. First, our model assumes that the regulator takes the policy regime as given. In richer environments, however, the social planner could choose between a flexible and inflexible policy in the first stage of the game. Such decision could nonetheless convey additional information to the potential entrant, thus modifying our equilibrium predictions. Second, we consider that production generates a flow externality. If, in contrast, pollution does not fully dissipate across time, i.e., stock externality, first-period taxes would be more stringent in order to mitigate the future damage of pollution, potentially affecting entry decisions under inflexible policies.

8 Appendix

8.1 *Proof of Lemma 1*

Let us first separately find the deadweight loss from committing to a constant fee t in the first period, DWL_1, and in the second period, DWL_2. We focus on the case in which the incumbent's costs are high, and thus entry ensues in the complete information game. When the incumbent's costs are low, entry does not occur, and the regulator just needs to set a fee $t^{L,NE} = (2d-1)q_{SO}^K$. Hence, when costs are high, the first-period deadweight loss from setting an inefficient fee t is

$$DWL_1(t) \equiv \int_{q^H(t)}^{q_{SO}^H} \left[MB^{H,NE}(q) - MD^{NE}(q)\right] dq$$

where socially optimal output q_{SO}^H is $q_{SO}^H = \frac{1-c_{inc}^H}{1+2d}$, and the monopolist output function is $q^H(t) = \frac{1-\left(c_{inc}^H+t\right)}{2}$. In addition, the benefit from a marginal increase in output is $MB^{H,NE}(q) = (1-q)-c_{inc}^H$, whereas its associated marginal environmental damage is $MD^{NE}(q) = 2dq$. Integrating, we obtain

$$DWL_1(t) = \frac{\left[(2d-1)c_{inc}^H + 1 + t - 2d(1-t)\right]^2}{8A}$$

where $A \equiv 1+2d$. In the second-period game, the deadweight loss from the inflexible fee t is

$$DWL_2(t) \equiv \int_{X^{H,E}(t)}^{X_{SO}^H} \left[MB^{H,E}(X) - MD^E(X)\right] dX,$$

where socially optimal output is still $X_{SO}^H = \frac{1-c_{inc}^H}{1+2d}$, and $X^{H,E}(t) = x_{inc}^{H,E}(t) + x_{ent}^{H,E}(t)$, where $x_{inc}^{H,E}(t) = x_{ent}^{H,E}(t) = \frac{1-\left(c_{inc}^H+t\right)}{3}$ represent the output function that each firm uses to respond to fee t under duopoly. (Note that since the incumbent's costs are high, we have $c_{inc}^H = c_{ent}$, and both firms' production functions coincide.) Furthermore, $MB^{H,E}(X) = (1-X) - c_{inc}^H$, whereas $MD^{NE}(X) = 2dX$. Integrating, we obtain

$$DWL_2(t) = \frac{\left[(4d-1)c_{inc}^H + 2 + 2t - 4d(1-t) - 1\right]^2}{18A}$$

The regulator can construct the discounted sum $DWL_1(t)+\delta DWL_2(t)$ (note that both $DWL_1(t)$ and $DWL_2(t)$ are strictly positive) and take first-order conditions with respect to t, obtaining $t^{H,E} = \frac{(1-c_{inc}^H)[8\delta 2dG-G]}{AG}$ where $G \equiv 9+16\delta$. In the case of no discounting, $\delta = 1$, fee $t^{H,E}$ becomes $t^{H,E} = \frac{(1-c_{inc}^H)[50d-17]}{25A}$. Note that the emission fee $t^{H,E}$ yields the minimum of the objective function $DWL_1(t) + \delta DWL_2(t)$ since such objective function is convex in t, i.e., $\frac{\partial^2[DWL_1(t)+\delta DWL_2(t)]}{\partial t^2} = \frac{AG}{36} > 0$ for all parameter values.

Finally, fee $t^{H,E}$ can be expressed as a linear combination of the socially optimal fees that the regulator would select if he had the ability to redesign emission fees across time (flexible policy regime), $t_1^H = (2d-1)\frac{1-c_{inc}^H}{1+2d}$ in the first period and $t_2^{H,E} = (4d-1)\frac{1-c_{inc}^H}{4(1+2d)}$ in the second period.

Specifically, the weights on fees t_1^H and $t_2^{H,E}$ can be found by solving $t^{H,E} = \alpha t_1^H + (1-\alpha)t_2^{H,E}$, where parameter α describes the relative weight on first-period taxes. For the case in which $\delta = 1$, parameter $\alpha = \frac{9}{25}$. Hence, $t^{H,E} = \frac{9}{25}t_1^H + \frac{16}{25}t_2^{H,E}$, and thus $t_1^H < t^{H,E} < t_2^{H,E}$. From the analysis of emission fees under a flexible policy regime in Lemma 1 of Espinola-Arredondo and Munoz-Garcia (2012), we know that fee $t_2^{H,E}$ is positive and induces positive output levels from both firms in the industry as long as firms' costs are not extremely different, i.e., $c_{inc}^L < c_{inc}^H < \frac{1+2dc_{inc}^L}{1+2d}$. Therefore, a lower fee $t^{H,E}$ in the inflexible policy regime must also induce positive production levels from both incumbent and entrant. ■

8.2 *Proof of Proposition 1*

We show that the only sustainable informative strategy profile in equilibrium involves both the incumbent and the regulator selecting type-dependent strategies. The first part of the proof demonstrates that the strategy profile where only the incumbent chooses a type-dependent strategy cannot be supported as a PBE. The second part shows that the converse strategy profile, where only the regulator chooses a type-dependent strategy, cannot be sustained as a PBE. The last part demonstrates that strategy profiles in which both regulator and incumbent select type-dependent strategies can be supported as PBE.

Information revealed by the incumbent. First, we show that an informative strategy profile where only the incumbent selects a type-dependent output function cannot be sustained as an equilibrium. In particular, consider the case in which the regulator chooses a type-independent tax t' (constant across time) whereas the incumbent selects a type-dependent output function: $q^H(t)$ when her costs are high, and $q^{L,sep}(t)$ when her costs are low for any given tax t. After observing equilibrium output levels $q^H(t')$ and $q^{L,sep}(t')$, entrant's equilibrium beliefs are $\mu(c_{inc}^H|q^H(t'),t') = 1$ and $\mu(c_{inc}^H|q^{L,sep}(t'),t') = 0$, respectively.

Note that deviations towards different emission fees $t'' \neq t'$ do not affect the information transmitted to the entrant through output levels $q^H(t'')$ and $q^{L,sep}(t'')$. Indeed, after observing a tax t'', the entrant can still check that the incumbent's output level coincides with $q^H(t'')$ (inducing him to enter) or with $q^{L,sep}(t'')$ (deterring him from entry). Hence, the entrant's beliefs, after observing the off-the-equilibrium fee t'', are $\mu(c_{inc}^H|q^H(t''),t'') = 1$ and $\mu(c_{inc}^H|q^{L,sep}(t''),t'') = 0$.

If, in contrast, the incumbent selects an off-the-equilibrium output function $q(t) \neq q^H(t) \neq q^{L,sep}(t)$, the entrant observes an output level that, for an announced tax t, neither coincides with $q^H(t)$ nor with $q^{L,sep}(t)$. In this case, the entrant cannot infer the incumbent's type after observing the type-independent fee t and output level $q(t)$, and thus her off-the-equilibrium beliefs are $\mu(c_{inc}^H|q(t),t) = 1$, which holds for any fee t.

Operating backwards, let us first analyze the incumbent's output choice for any given tax t. When her marginal costs are high, the incumbent selects the first-period profit-maximizing output, $q^H(t)$. If the incumbent deviates towards the low-cost incumbent's output $q^{L,sep}(t)$, she deters entry. Hence, the high-cost incumbent selects her equilibrium output function $q^H(t)$ if

$M^H_{inc}(q^H(t),t) + \delta D^H_{inc}(t) \geq M^H_{inc}(q^{L,sep}(t),t) + \delta \overline{M}^H_{inc}(t)$ or equivalently,

$$M^H_{inc}(q^H(t),t) - M^H_{inc}(q^{L,sep}(t),t) \geq \delta \left[\overline{M}^H_{inc}(t) - D^H_{inc}(t) \right] \tag{C1}$$

Likewise, if the low-cost incumbent chooses the equilibrium output function $q^{L,sep}(t)$, she deters entry. If instead the incumbent deviates towards the high-cost incumbent's output function, $q^H(t)$, she attracts entry. Conditional on entry, the low-cost incumbent can select an off-the-equilibrium output $q(t) \neq q^H(t) \neq q^{L,sep}(t)$ that achieves a higher profit than that associated to $q^H(t)$. In this case, the incumbent selects an output $q^L(t)$, where $q^L(t) < q^{L,sep}(t)$, which maximizes her profits prior to entry, yielding $M^L_{inc}(q^L(t),t) + \delta D^L_{inc}(t)$. Thus, the low-cost incumbent selects her equilibrium output of $q^{L,sep}(t)$ if $M^L_{inc}(q^{L,sep}(t),t) + \delta \overline{M}^L_{inc}(t) \geq M^L_{inc}(q^L(t),t) + \delta D^L_{inc}(t)$, or equivalently,

$$M^L_{inc}(q^L(t),t) - M^L_{inc}(q^{L,sep}(t),t) \leq \delta \left[\overline{M}^L_{inc}(t) - D^L_{inc}(t) \right] \tag{C2}$$

In addition, the regulator must prefer to set the same per-unit tax to both types of incumbents, i.e., $t = t'$. Note that, given the type-dependent strategy profile of the incumbent, the regulator's decision cannot conceal the incumbent's type from the entrant. Therefore, the regulator sets a first-period tax $t = t'$ if,

$$SW^{H,E}(t') \geq SW^{H,E}(t^{H,E}) \text{ and } SW^{L,NE}(t') \geq SW^{L,NE}(t^{L,NE}) \tag{C3}$$

However, the first inequality in condition C3 cannot hold. Conditional on entry, the regulator would reduce social welfare by imposing an emission fee $t' \neq t^{H,E}$, which exacerbates the inefficiencies beyond those arising under complete information. Hence, this type of strategy profile cannot be sustained as a PBE of the game.

Information revealed by the regulator. Let us now analyze the case where the regulator selects type-dependent emission fees $(t^{H,E}, t^{L,sep})$ while the incumbent chooses a type-independent output function $q(t)$. After observing equilibrium output levels $q(t^{H,E})$ and $q(t^{L,sep})$, entrant's equilibrium beliefs are $\mu(c^H_{inc}|q(t^{H,E}), t^{H,E}) = 1$ and $\mu(c^H_{inc}|q(t^{L,sep}), t^{L,sep}) = 0$, respectively. Likewise, the entrant's off-the-equilibrium beliefs are $\mu(c^H_{inc}|q'(t^{H,E}), t^{H,E}) = 1$ and $\mu(c^H_{inc}|q'(t^{L,sep}), t^{L,sep}) = 0$ after observing emission fee $t^{H,E}$ and $t^{L,sep}$ for any output function $q'(t) \neq q^H(t) \neq q^{L,sep}(t)$. Furthermore, after observing an off-the-equilibrium fee $t' \neq t^{H,E} \neq t^{L,sep}$ and output level $q(t')$, the entrant's beliefs are $\mu(c^H_{inc}|q(t'), t') = 1$. And his beliefs are $\mu(c^H_{inc}|q'(t'), t') = 1$ after observing off-the-equilibrium fee t' and off-the-equilibrium output function $q'(t) \neq q(t)$. For any given emission fee $t \neq t^{L,sep}$ entry ensues, and the high-cost incumbent selects $q(t)$ if $M^H_{inc}(q(t),t) + \delta D^H_{inc}(t) \geq M^H_{inc}(q^H(t),t) + \delta D^H_{inc}(t)$, which cannot hold since $q^H(t)$ maximizes her first-period monopoly profits. Therefore, this type of strategy profile cannot be sustained as a PBE of the game.

Information revealed by both agents. Let us finally examine the case where both regulator and incumbent select type-dependent strategy profiles. In particular, the regulator chooses emission fees $(t^{H,E}, t^{L,sep})$ where $t^{L,sep} \geq t^{L,NE}$ and the incumbent selects output function $q^H(t)$ when her costs are high and $q^{L,sep}(t)$ when her costs are low.

- *High-cost incumbent.* After observing emission fee $t^{H,E}$, the incumbent selects output level $q^H\left(t^{H,E}\right)$ since $M^H_{inc}(q^H(t^{H,E}),t^{H,E})+\delta D^H_{inc}(t^{H,E})\geq M^H_{inc}(q^{L,sep}(t^{H,E}),t^{H,E})+\delta D^H_{inc}(t^{H,E})$ holds given that $q^H(t^{H,E})$ maximizes first-period profits. In particular, after observing fee $t^{H,E}$ but output level $q^{L,sep}(t^{H,E})$, the entrant's beliefs are $\mu(c^H_{inc}|q^{L,sep}(t^{H,E}),t^{H,E})=1$. A similar argument holds for the case in which emission fee $t^{H,E}$ is followed by deviations to any off-the-equilibrium output function $q(t)\neq q^H(t)\neq q^{L,sep}(t)$, where the entrant's beliefs also induce him to enter. Therefore, after observing any emission fee $t\neq t^{H,E}$, the high-cost incumbent chooses $q^H(t)$ if

$$M^H_{inc}(q^H(t),t)+\delta D^H_{inc}(t)\geq M^H_{inc}(q^{L,sep}(t),t)+\delta\overline{M}^H_{inc}(t) \quad \text{(C1)}$$

  where entry is deterred when she selects $q^{L,sep}(t)$ since $\mu(c^H_{inc}|q^{L,sep}(t),t)=0$ for all $t\neq t^{H,E}$. This holds not only for the equilibrium fee $t=t^{L,sep}$, but also for any off-the-equilibrium fee t'' since, after observing t'', the entrant only relies on output level $q^{L,sep}(t'')$ to infer the incumbent's type.

- *Low-cost incumbent.* The incumbent selects output level $q^{L,sep}(t^{L,sep})$ after observing the equilibrium emission fee $t^{L,sep}$ if

$$M^L_{inc}(q^{L,sep}(t^{L,sep}),t^{L,sep})+\delta\overline{M}^L_{inc}(t^{L,sep})\geq M^L_{inc}(q^H(t^{L,sep}),t^{L,sep})+\delta D^L_{inc}(t^{L,sep})$$

  is satisfied. A similar argument holds for the case in which emission fee $t^{L,sep}$ is followed by deviations to any off-the-equilibrium output function $q(t)\neq q^H(t)\neq q^{L,sep}(t)$. Conditional on entry, the most profitable deviation is $q^L(t^{L,sep})$. Hence, the low-cost incumbent chooses $q^{L,sep}(t^{L,sep})$ if

$$M^L_{inc}(q^{L,sep}(t^{L,sep}),t^{L,sep})+\delta\overline{M}^L_{inc}(t^{L,sep})\geq M^L_{inc}(q^L(t^{L,sep}),t^{L,sep})+\delta D^L_{inc}(t^{L,sep})$$

  where the entrant infers that the incumbent's costs must be low since output level $q^{L,sep}(t^{L,sep})$ is consistent with emission fee $t^{L,sep}$. A similar argument is applicable for any off-the-equilibrium emission fee $t\neq t^{H,E}\neq t^{L,sep}$,

$$M^L_{inc}(q^{L,sep}(t),t)+\delta\overline{M}^L_{inc}(t)\geq M^L_{inc}(q^L(t),t)+\delta D^L_{inc}(t) \quad \text{(C2)}$$

  since in this case the entrant only relies on the observed output level to infer the incumbent's type. After observing $t^{H,E}$, the low-cost incumbent selects $q^{L,sep}(t^{H,E})$ if $M^L_{inc}(q^{L,sep}(t^{H,E}),t^{H,E})+\delta D^L_{inc}(t^{H,E})\geq M^L_{inc}(q^L(t^{H,E}),t^{H,E})+\delta D^L_{inc}(t^{H,E})$ since, given entry, $q^L(t^{H,E})$ maximizes the incumbent's first-period profits. However, this condition cannot hold, and therefore the low-cost incumbent selects $q^{L,sep}(t)$ for fee $t\neq t^{H,E}$, but $q^L(t)$ otherwise.

- *Regulator.* He chooses an emission fee $t^{H,E}$ when the incumbent's costs are high if $SW^{H,E}(t^{H,E})\geq$

$SW^{H,E}(t)$, which holds by definition for any fee $t \neq t^{H,E}$. Specifically, if condition C8 holds, the high-cost incumbent selects $q^H(t)$, which attracts entry regardless of the emission fee set by the regulator. If, in contrast, the incumbent's costs are low the regulator sets an emission fee t^A since, provided that condition C2 holds, the entrant stays out after observing output level $q^{L,sep}(t)$ for any fee $t \neq t^A$. Conditional on no entry, the regulator facing a low-cost incumbent selects an inflexible fee t that minimizes the discounted sum of deadweight losses (provided that the incumbent produces according to output function $q^A(t)$ in the first period and output function $x_{inc}^{L,NE}(t)$ in the second period). That is, the regulator solves

$$\min_{t} \; |DWL_1(t)| + \delta \, |DWL_2(t)|$$

where the deadweight loss of tax t in the first period is

$$DWL_1(t) \equiv \int_{q^{L,sep}(t)}^{q_{SO}^L} \left[MB^{L,NE}(q) - MD^{NE}(q)\right] dq,$$

where $q^{L,sep}(t)$ denotes the output function selected by the low-cost incumbent in the first period; whereas the second-period deadweight loss is

$$DWL_2(t) \equiv \int_{x_{inc}^{L,NE}(t)}^{x_{SO}^L} \left[MB^{L,NE}(x) - MD^{NE}(x)\right] dx,$$

where $x_{inc}^{L,NE}(t)$ represents the incumbent's second-period production function when entry does not ensue, and $x_{inc}^{L,NE}(t) = q^L(t)$.

By a similar argument as in the proof of Lemma 2 in Espinola-Arredondo and Munoz-Garcia (2012), it is easy to show that only the informative equilibrium where the regulator sets a tax pair $\left(t^{H,E}, t^A\right)$, the high-cost incumbent selects an output function $q^H(t)$, and the low-cost incumbent chooses output function $q^{L,Sep}(t) = q^A(t)$, where $q^A(t)$ solves condition C8 with equality, survives the Cho and Kreps' Intuitive Criterion, i.e., $q^A(t) = \frac{(1-c_{inc}^H-t)(3+\sqrt{5}\sqrt{\delta})}{6}$, where $q^A(t)$ satisfies the low-cost incumbent's incentive compatibility condition C2 as long as $c_{inc}^H = c_{ent} < \beta \equiv \frac{(3\sqrt{5}-5)(1-c_{inc}^L)+2(1+2d)c_{inc}^L}{2(1+2d)}$. ■

8.3 *Proof of Corollary 1*

Informative equilibrium vs. Complete information. The informative equilibrium induces an output level of $q^A(t^A)$, which exceeds that under complete information, $q^L(t^{L,NE})$, where $q^L(t^{L,NE}) = q_{SO}^L$. Then, the first-period overproduction in the informative equilibrium of Proposition 1, i.e., $q^A(t^A) > q_{SO}^L$, entails a welfare loss. Similarly, in the second period, the incumbent maintains its monopoly power, producing according to output function $x_{inc}^{L,NE}(t)$, which coincides with production function $q^L(t)$. Under complete information, the inflexible fee $t^{L,NE}$ induces a socially optimal output in this period since $x_{inc}^{L,NE}(t^{L,NE}) = q^L(t^{L,NE}) = q_{SO}^L$. In contrast, under the informative equilibrium, the more stringent fee t^A induces a lower output level, i.e., $x_{inc}^{L,NE}(t^A) < q_{SO}^L$ since $t^A > t^{L,NE}$. Therefore, output is socially efficient during both periods under complete information but experiences an increase (decrease) in the first period (second period, respectively) under the informative equilibrium. Therefore, the introduction of incomplete information yields output inefficiencies during both time periods, thus entailing an overall welfare loss.

Informative equilibrium with and without regulator. Without regulation, the low-cost incumbent sets its first-period output function at $q^A(0)$, while second-period output is $x_{inc}^{L,NE}(0) = q^L(0)$. When the regulator is present, however, first-period output decreases to $q^A(t^A)$, where

$$q^A(0) > q^A(t^A) > q_{SO}^L,$$

whereas second-period output decreases to $x_{inc}^{L,NE}(t^A)$, where

$$x_{inc}^{L,NE}(t^A) < q_{SO}^L < x_{inc}^{L,NE}(0).$$

Since the presence of the regulator ameliorates the environmental externality (and such market failure dominates that arising from the market monopolization given that $d > 1/2$), the reduction in output during both periods entails an increase in social welfare. ■

8.4 *Proof of Proposition 2*

In the uninformative strategy profile, the regulator sets a type-independent emission fee t' and the incumbent selects a type-independent first-period output function $q(t)$ for any emission fee t. After observing equilibrium fee t' and output level $q(t')$, entrant's equilibrium beliefs are $\mu(c_{inc}^H|q(t'), t') = p$, which coincide with the prior probability distribution. After observing a deviation from the regulator to $t'' \neq t'$, the entrant's off-the-equilibrium beliefs cannot be updated using Bayes' rule and, for simplicity, we assume that $\mu(c_{inc}^H|q(t''), t'') = 1$. A similar argument can be made in the case where only the incumbent deviates towards an output function $q'(t') \neq q(t')$ while the regulator still selects t', i.e., $\mu(c_{inc}^H|q'(t'), t') = 1$. The same is true when both informed agents deviate, i.e., $\mu(c_{inc}^H|q'(t''), t'') = 1$.

Therefore, after observing an equilibrium emission fee t' and an equilibrium output level $q(t')$, the entrant enters if his expected profit from entering satisfies $p \times D_{ent}^H(t') + (1-p) \times D_{ent}^L(t') - F > 0$ or $p > \frac{F - D_{ent}^L(t')}{D_{ent}^H(t') - D_{ent}^L(t')} \equiv \overline{p}(t')$. Hence, if $p > \overline{p}(t')$ entry occurs; otherwise the entrant stays out. Note that if $p > \overline{p}(t')$, entry occurs after t' and $q(t')$ are selected, which cannot be optimal for both types of incumbent, inducing them to select $q^K(t')$. But since $q^H(t') \neq q^L(t')$ this strategy cannot be a pooling equilibrium. Thus, it must be that $p \leq \overline{p}(t')$, inducing the entrant to stay out.

High-cost incumbent. Let us check the conditions under which the high-cost incumbent chooses output function $q(t)$. After observing an equilibrium emission fee of t', the high-cost incumbent obtains profits $M_{inc}^H(q(t'), t') + \delta \overline{M}_{inc}^H(t')$. If, instead, the incumbent deviates towards an off-the-equilibrium output $q'(t') \neq q(t')$, entry ensues and her profits become $M_{inc}^H(q'(t'), t') + \delta D_{inc}^H(t')$, which are maximized at $q'(t') = q^H(t')$. Hence, the high-cost incumbent selects $q(t')$ if

$M_{inc}^{H}(q(t'),t') + \delta\overline{M}_{inc}^{H}(t') \geq M_{inc}^{H}(q^{H}(t'),t') + \delta D_{inc}^{H}(t')$, or alternatively

$$\delta\left[\overline{M}_{inc}^{H}(t') - D_{inc}^{H}(t')\right] \geq M_{inc}^{H}(q^{H}(t'),t') - M_{inc}^{H}(q(t'),t') \tag{C4}$$

After observing an off-the-equilibrium fee $t'' \neq t'$, entry ensues regardless of the incumbent's output function, and therefore $M_{inc}^{H}(q(t''),t'') + \delta D_{inc}^{H}(t'') \geq M_{inc}^{H}(q^{H}(t''),t'') + \delta D_{inc}^{H}(t'')$ cannot hold by definition.

Low-cost incumbent Similarly for the low-cost incumbent. If, after observing equilibrium fee t', she selects equilibrium output level $q(t')$, her profits are $M_{inc}^{L}(q(t'),t') + \delta\overline{M}_{inc}^{L}(t')$. However, if she deviates towards $q'(t')$ entry ensues, obtaining profits $M_{inc}^{L}(q'(t'),t') + \delta D_{inc}^{L}(t')$, which are maximized at $q'(t') = q^{L}(t')$. Hence, the low-cost incumbent chooses $q(t')$ if $M_{inc}^{L}(q(t'),t') + \delta\overline{M}_{inc}^{L}(t') \geq M_{inc}^{L}(q^{L}(t'),t') + \delta D_{inc}^{L}(t')$, or alternatively

$$\delta\left[\overline{M}_{inc}^{L}(t') - D_{inc}^{L}(t')\right] \geq M_{inc}^{L}(q^{L}(t'),t') - M_{inc}^{L}(q(t'),t') \tag{C5}$$

After observing an off-the-equilibrium fee $t'' \neq t'$, entry ensues regardless of the incumbent's output function, and therefore, $q(t'')$ is not optimal for the low-cost firm.

Regulator. Let us now examine the regulator's incentives to choose a type-independent emission fee t'. When the incumbent's costs are high, the regulator obtains $SW^{H,NE}(t')$ by selecting t'. If, instead, he deviates to any off-the-equilibrium fee $t'' \neq t'$, the incumbent selects $q^{H}(t'')$ and entry ensues. Hence, he obtains $SW^{H,E}(t'')$, which is maximized at $t^{H,E}$. Thus, the regulator chooses t' if

$$SW^{H,NE}(t') \geq SW^{H,E}(t^{H,E}). \tag{C6a}$$

When the incumbent's costs are low, the regulator obtains $SW^{L,NE}(t')$ by selecting the type-independent t'. If instead, he deviates to t'', the incumbent selects $q^{L}(t'')$ and entry follows. The regulator's social welfare is therefore maximized at $t'' = t^{L,E}$, yielding $SW^{L,E}(t^{L,E})$. Thus, the regulator chooses t' if

$$SW^{L,NE}(t') \geq SW^{L,E}(t^{L,E}). \tag{C6b}$$

Therefore, any emission fee t' and output function $q(t)$ simultaneously satisfying conditions C4-C6 constitutes an uninformative equilibrium of the signaling game. Using an argument similar to the proof of Lemma 3 in Espinola-Arredondo and Munoz-Garcia (2012), it is straightforward to show that the only uninformative PBE surviving the Cho and Kreps' Intuitive Criterion is that where the regulator selects a constant fee $t' = t^{L,NE}$ and the high-cost incumbent chooses output function $q(t) = q^{L}(t)$ when priors satisfy $p \leq \overline{p}(t^{L,NE})$

Therefore, condition C6b for the regulator holds by definition. In particular, conditional on no entry, fee $t^{L,NE}$ induces socially optimal output levels while, conditional on entry, fee $t^{H,E}$ generates inefficiencies in both periods, thus implying that $SW^{L,NE}(t^{L,NE}) > SW^{H,E}(t^{H,E})$. In contrast, condition C6a (evaluated at the equilibrium fee $t^{L,NE}$ and output level $q^{L}(t^{L,NE})$), i.e.,

$SW^{L,NE}(t^{L,NE}) \geq SW^{L,E}(t^{L,E})$, is satisfied for all entry costs $F > F^{Inflex}(d)$, where

$$F^{Inflex}(d) \equiv \frac{[121+100(d-1)d]\left(c_{inc}^{H}\right)^{2}+25B\left(c_{inc}^{L}\right)^{2}+c_{inc}^{H}\left[8-50Bc_{inc}^{L}\right]-4}{200(1+2d)}$$

and $B \equiv 5+4(d-1)d$. ■

8.5 *Proof of Corollary 2*

Uninformative equilibrium vs. Complete information. The equilibrium emission fee under complete information, $t^{H,E}$, entails a first-period output $q^{H}(t^{H,E})$, which is lower than the socially optimal output q_{SO}^{H} given that fee $t^{H,E}$ is more stringent than the optimal fee, that a regulator with the ability to redesign fees across time (flexible policy regime), would set. In particular, he would select a first-period fee $t_1^H = (2d-1)\frac{1-c_{inc}^{H}}{1+2d}$ that induces $q^H(t_1^H) = q_{SO}^H$, where $q^H(t_1^H) > q^H(t^{H,E})$ since fees satisfy $t_1^H < t^{H,E}$. In the second-period, fee $t^{H,E}$ yields an aggregate output of $x_{inc}^{H,E}(t^{H,E})+x_{ent}^{H,E}(t^{H,E})$, which exceeds the socially optimal output $X_{SO}^{H} = x_{inc}^{H,E}(t_2^{H,E})+x_{ent}^{H,E}(t_2^{H,E})$, since $t^{H,E} < t_2^{H,E}$, where $t_2^{H,E} = (4d-1)\frac{1-c_{inc}^{H}}{4(1+2d)}$ represents the optimal fee that a regulator would set under a flexible policy regime in order to induce an aggregate output level that coincides with the social optimum; for more details on this fee, see the proof of Lemma 1 in Espinola-Arredondo and Munoz-Garcia (2012). A similar argument is applicable under the uninformative equilibrium, where the regulator does not induce socially optimal output either. In particular, the equilibrium fee of $t^{L,NE}$ induces a first-period output of $q^L(t^{L,NE})$, which exceeds the socially optimal output $q^H(t_1^H) = q_{SO}^H$ since $q^L(t^{L,NE}) - q_{SO}^H = \frac{c_{inc}^H - c_{inc}^L}{A}$. Analogously, in the second period, the equilibrium fee $t^{L,NE}$ entails an output level of $x_{inc}^{H,NE}(t^{L,NE})$, which lies below the efficient production level $q^H(t_1^H) = q_{SO}^H$ since output functions $x_{inc}^{H,NE}(t)$ and $q^H(t)$ coincide but fee t_1^H satisfies $t_1^H < t^{L,NE}$. Therefore, inefficiencies arise under both information contexts. However, as we know from Proposition 2, the equilibrium fee in the uninformative equilibrium $t^{L,NE}$ yields a welfare level, $SW^{L,NE}(t^{L,NE})$, above that of setting fee $t^{H,E}$ that attracts entry, $SW^{L,E}(t^{L,E})$, when entry costs satisfy $F > F^{Inflex}(d)$; a condition that must hold for the uninformative equilibrium to be sustained. Hence, if the uninformative equilibrium emerges, its associated social welfare exceeds that under complete information (where entry occurs).

Informative equilibrium with and without regulator. Without regulation, the high-cost incumbent sets its first-period output function at $q^L(0)$ in order to mimic the production decision of the low-cost firm, while her second-period output is $x_{inc}^{H,NE}(0) = q^H(0)$. When the regulator is present, however, first-period output decreases to $q^L(t^{L,NE})$, where

$$q^L(0) > q^L(t^{L,NE}) > q_{SO}^H = q^H(t^{H,NE}),$$

whereas second-period output decreases to $x_{inc}^{H,NE}(t^{L,NE})$, where

$$x_{inc}^{L,NE}(t^{L,NE}) = q^H(t^{L,NE}) < q_{SO}^H = q^H(t^{H,NE}) < q^H(0)$$

given that $t^{L,NE} > t^{H,NE}$. Therefore, the presence of the regulator ameliorates the environmental externality in both periods, entailing a welfare improvement. ■

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