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Promoting Lies through Regulation:

Deterrence Impacts of Flexible versus Inflexible Policy[*]

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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 study contexts in which tax policy is flexible and inflexible. We show that not only an informative equilibrium can be supported where information is conveyed to the entrant, but also an uninformative equilibrium where information is concealed. In addition, flexible policies promote information transmission. Therefore, our results identify a potential benefit of flexible policies, namely, hampering firms' ability to practice entry deterrence.

Keywords: Entry deterrence; Signaling; Emission fees; Inflexible Policy.

JEL classification: D82, H23, L12, Q5

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1 Introduction

Monopolies often engage in practices that deter the entry of potential competitors. Standard limit-pricing models study such a strategy, whereby the incumbent firm overproduces in order to signal her cost structure to potential entrants. The monopolist's actions, however, do not occur in a vacuum. Indeed, the incumbent might be regulated by government agencies that accumulate relatively accurate information about the incumbent's cost structure over time. This is especially true for polluting firms that have maintained a strong monopolistic position for a long period of time while facing emission fees from an environmental protection agency. Coal-fired power plants, for instance, are usually considered regional monopolies that have continually faced environmental regulations from the U.S. Environmental Protection Agency (EPA).[1] More generally, in the case of polluting firms that were publicly owned and managed, but recently privatized, the regulator may hold precise information about their cost structure, while the entrant does not.[2]

Alternatively, this information structure illustrates settings where firms face different administrative costs of complying with the environmental regulation, as empirically reported by Monty (1991) and Dean and Brown (1995), and they are asymmetrically informed about these costs. In particular, after operating in the industry during several years, the incumbent firm can assess both its own administrative costs as well as those of the potential entrant, whereas the latter can only estimate its own costs. Unlike the entrant, the regulator can easily infer firms' compliance costs, since polluters must recurrently interact with him in order to fulfill the requirements imposed by the environmental policy.[3]

In order to examine agents' strategic behavior, we must hence consider information structures whereby the regulator and incumbent have access to more accurate information than the entrant. Importantly, in this context potential entrants not only observe the incumbent's output but also the regulation recently faced by that incumbent. Information about the incumbent's cost structure is, therefore, conveyed or concealed from the entrant depending on *both* regulation and output, rather than merely through output as in standard entry-deterrence models. This introduces a new role for emission fees, since they can serve as environmental policies to mitigate pollution as well as antitrust policies that facilitate entry, or trust-promoting policies that hinder such entry.

Our paper examines an entry-deterrence model with signaling where an informed regulator imposes an emission fee in each period. We first allow the regulator to revise his environmental policy if the market structure changes —which describes institutional settings where policy rapidly

[1] For example, the Clean Air Act of 1963 and its subsequent amendments in 1970 and 1990 aimed at reducing NOx emissions, as well as the more drastic policy issued by the EPA in September 1998.

[2] 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 Petro-Canada (1991) in Canada.

[3] The cost asymmetry among firms can stem from technological or managerial reasons. For instance, incumbent and entrant might access the same technology and work force, but differ in their managerial abilities, inducing different production costs. This managerial ability is observed by the incumbent and the regulator given their recurrent interaction, but unobserved by the entrant.

adapts to changing market conditions, i.e., *flexible* policy— and then restrict the regulator's choice to a constant emission fee, which represents environmental protection agencies that, instead, do not frequently adjust their regulation to industry conditions, referred to as *inflexible* policy. In the signaling game we find two types of equilibria: an informative equilibrium, where information about the incumbent's cost efficiency is fully revealed to the entrant, and an uninformative equilibrium, where information is concealed.

Under a flexible policy, the informative equilibrium shows that the introduction of environmental regulation facilitates the transmission of information from the efficient incumbent to the entrant. In particular, the standard incumbent's "overproduction" result found in the literature on limit pricing is ameliorated in our context. Intuitively, the existence of an emission fee reduces the efficient incumbent's entry-deterrence benefits and thus, her incentive to signal her type in order to deter entry.

In addition, we demonstrate that the introduction of incomplete information does not affect social welfare, since the regulator designs environmental policy in order to induce socially optimal output levels under both information contexts. Our results, hence, differ from those in standard entry-deterrence models, whereby the incumbent's production approaches the socially optimal output, but still generates a sub-optimal welfare.

Under this flexible policy regime, we also show that an uninformative equilibrium can be supported, where both the regulator and incumbent conceal information by selecting type-independent strategies, thus deterring entry. Specifically, the inefficient incumbent increases her output in order to mimic that of the efficient type, i.e., she "overproduces." Similarly, the regulator raises emission fees to make them coincide with those imposed on an efficient firm, i.e., the regulator "overtaxes." Hence, both regulator and incumbent are willing to give up some of their first-period payoff in order to deter entry. Intuitively, this suggests that both informed players must be willing to share the burden of concealing information from the entrant. Such concealment strategy, however, does not necessarily entail a welfare loss relative to complete information contexts. In fact, our findings show that the regulator is only willing to practice such strategy if it yields a larger welfare than under complete information, which occurs when the welfare loss from over-taxation is sufficiently low, i.e., when the environmental damage from pollution is large.

We then examine entry deterrence when emission fees are constant over time, i.e., inflexible policy. In this institutional setting, we show that both informative and uninformative strategy profiles can be supported. A constant fee, however, entails inefficient output levels both under complete and incomplete information, implying that the regulator must choose between two sub-optimal situations, i.e., second-best regulation.

We finally evaluate the impact of policy commitment on information transmission. In the informative equilibrium, we show that the incumbent's entry-deterrence benefits are higher under a flexible environmental policy. This is due to the more stringent emission fees that are imposed on duopolists, thus raising the incentives of the inefficient firm to mimic the output decision of the efficient type. Therefore, the efficient firm needs to exert more effort (further overproduce) in order to convey her type to the potential entrant, suggesting that communication becomes more difficult under flexible emission fees. Nonetheless, flexible policies sustain the informative equilibrium under larger conditions than inflexible policies.

From a policy perspective, our results suggest that the regulator should pursue flexible environmental policies if he seeks to 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 set of parameter values under which entry-deterrence can be supported. Therefore, our findings identify a benefit of environmental protection agencies often overlooked by the environmental regulation literature. Agencies that adjust their policies to market conditions rapidly shrink the parameter conditions under which incumbent firms can practice entry deterrence.

Our analysis is not confined to the field of environmental economics. For instance, the model is applicable to settings where public goods are promoted through subsidies. In such a case, the potential entrant would base his entry decision on an observed subsidy and the incumbent's output level. Similarly, the model may be applied to the field of international trade, where tariff policy and output serve as signals to uninformed foreign firms seeking to sell their goods in the domestic market.

Related literature. This paper contributes to three areas of the literature: entry-deterrence models, environmental policy under incomplete information, and papers analyzing flexible and inflexible policies. 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.[4] 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.

[4] 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.

In the field of capital-structure decisions, Gertner et al. (1988) analyze an enlarged entry deterrence model where the informed firm sends a signal about its profitability to two uninformed agents: the capital and product market. In particular, they show that the emergence of the separating or pooling equilibrium in the capital market critically depends on whether the incumbent is interested in revealing or concealing her type to the product market. Hence, separating or pooling equilibria are endogenous. Similarly, in our paper, the emergence of the informative or uninformative equilibrium depends on whether the regulator seeks to attract or deter entry, respectively.

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). However, these studies do not consider the signaling role of environmental policy. Antelo and Loureiro (2009) also assume that the regulator cannot observe the incumbent's costs, but infers her type from first-period output and, as in our paper, the incumbent's separating effort is ameliorated in their setting. Despite such similarity, our model and results differ along several dimensions. First, we consider situations where the regulator has accumulated accurate information about the incumbent's cost structure over time. This allows for emission fees to play a signaling role.[5] Second, our paper provides a comparison of flexible and inflexible policies under signaling contexts. Lastly, our results analyze both separating and pooling equilibria and focus on those equilibria surviving standard equilibrium refinements.

Finally, the paper contributes to the literature comparing flexible and inflexible policies. Since the initial work by Kydland and Prescott (1977) and Barro and Gordon (1983), several papers examined commitment in monetary policy, Chang (1998) and Alvarez et al. (2004), in capital tax policy, Judd (1985) and Benhabib et al. (2001), and in both, Dixit and Lambertini (2003). These papers, however, consider a context of complete information where inflexible policies can be welfare improving under certain conditions.[6] In contrast, we present an environment where an inflexible policy leads to welfare losses under complete information. Specifically, under a flexible policy players' actions do not have intertemporal effects, unlike the previous papers where monetary and capital tax policy affect future economic growth. We demonstrate, however, that under incomplete information benefits may arise from an inflexible environmental policy.

The next section describes the model under complete information, both in the case of flexible and inflexible policies. Section 3 examines the signaling game under a flexible policy while section 4 investigates that under an inflexible policy. At the end of section 4 we compare our equilibrium results with and without flexible policies, and section 5 concludes.

[5] 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.

[6] Similarly, Ko et al. (1992) compare flexible and inflexible environmental policies under complete information where a given set of firms produce stock externalities, i.e., pollution that does not fully dissipate across periods.

2 Model

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. The incumbent's constant marginal costs are either high H or low L, i.e., $c_{inc}^{H} > c_{inc}^{L} \geq 0$, where subscript inc denotes the incumbent. 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 selects a pollution tax t_1 per unit of output and the monopolist responds by choosing an output level q. In the second stage, a potential entrant decides whether or not to enter. The regulator then revises his environmental policy t_2 and if entry occurs firms compete as Cournot duopolists, simultaneously selecting production levels x_{inc} and x_{ent}, for the incumbent and entrant, respectively. Otherwise, the incumbent maintains its monopoly power during both periods. Let us next analyze optimal tax policy under a flexible setting, while section 2.2 examines the case of an inflexible tax.

2.1 Complete information under flexible policy

Second period. Let us first describe the second period. If entry does not occur, the incumbent's after-tax profits are

$$\pi_{inc}^{K,NE}(x_{inc}) \equiv \; p\left(x_{inc}\right) x_{inc} - c_{inc}^{K} x_{inc} - t_2 x_{inc}, \tag{1}$$

where $K = \{H, L\}$ represents the incumbent's type, NE denotes no entry, and the inverse demand function $p\left(x_{inc}\right)$ is linear in output and satisfies $p'\left(x_{inc}\right) < 0$ and $p\left(0\right) > c_{inc}^{K}$. If entry occurs, firms compete as Cournot duopolists in the second period. The profit functions for the incumbent and entrant are

$$\begin{aligned} \pi_{inc}^{K,E}(x_{inc}, x_{ent}) &\equiv \quad p\left(X\right) x_{inc} - c_{inc}^{K} x_{inc} - t_2 x_{inc} \text{ and} \\ \pi_{ent}^{K,E}(x_{inc}, x_{ent}) &\equiv \quad p\left(X\right) x_{ent} - c_{ent} x_{ent} - t_2 x_{ent} - F \end{aligned} \tag{2}$$

where $X = x_{inc} + x_{ent}$ represents the aggregate output level, superscript E denotes entry, c_{ent} is the entrant's marginal cost where $c_{ent} = c_{inc}^{H}$, and F represents the fixed entry cost. The regulator's social welfare function in the second period is

$$\begin{aligned} SW_2^{K,NE} &\equiv \quad CS(x_{inc}) + \pi_{inc}^{K,NE}(x_{inc}) + T_2^{K,NE} - d\left(x_{inc}\right) \quad \text{after no entry, and} \\ SW_2^{K,E} &\equiv \quad CS(X) + \pi_{inc}^{K,E}(x_{inc}, x_{ent}) + \pi_{ent}^{K,E}(x_{inc}, x_{ent}) - F + T_2^{K,E} - d\left(X\right) \quad \text{after entry} \end{aligned} \tag{3}$$

where $CS(x_{inc}) \equiv \int_0^{x_{inc}} p\left(x\right) dx - p(x_{inc}) x_{inc}$ represents the consumer surplus for a given output x_{inc} under monopoly and similarly $CS(X)$ for aggregate output X under duopoly. $T_2^{K,NE}$ reflects total tax revenues after no entry, while $T_2^{K,E}$ represents tax revenues upon entry.[7] In addition,

[7] Tax collection is therefore welfare neutral, since its negative effect on firms' profits is exactly offset by the positive effect of tax revenues.

$d(x_{inc})$ represents the strictly convex environmental damage from output, where $d'(x_{inc}) > 0$. Similar properties hold for $d(X)$ given the aggregate output X under entry. Furthermore, we assume that the marginal environmental damage satisfies $p(0) - c^K_{inc} > d'(0)$, which ensures that it is socially efficient to produce the first unit of output.

In the case of no entry, the regulator seeks to induce the socially optimal output $x^{K,NE}_{SO}$ which solves $MB^{K,NE}(x_{inc}) = MD^{NE}(x_{inc})$, where $MB^{K,NE}(x_{inc}) \equiv p(x_{inc}) - c$ represents the marginal benefit of additional output on consumer and producer surplus, which is decreasing in x_{inc}. In addition, $MD^{NE}(x_{inc}) \equiv d'(x_{inc})$ denotes the marginal environmental damage of output. The regulator imposes an emission fee $t^{K,NE}_2 = MP^{K,NE}_{inc}(x^{K,NE}_{SO})$ on monopoly output in order to induce the production level $x^{K,NE}_{SO}$ in the second period, where $MP^{K,NE}_{inc}(x_{inc})$ denotes the marginal profits of increasing x_{inc} given no entry.[8]

Under entry, the regulator aims to induce the aggregate socially optimal output $X^{K,E}_{SO}$ that solves $MB^{K,E}(X) = MD^E(X)$, where[9] $MB^{K,E}(X) \equiv p(X) - c^K_{inc}$ and $MD^E(X) \equiv d'(X)$. Hence, the emission fee $t^{K,E}_2$ that induces aggregate output $X^{K,E}_{SO}$ is $t^{K,E}_2 = MP^{K,E}_j\left(x^{K,E}_{j,SO}|x^{K,E}_{k,SO}\right)$ for all firm $j = \{inc, ent\}$ and $k \neq j$, where $MP^{K,E}_j\left(x_j|x^{K,E}_{k,SO}\right)$ denotes the marginal profit that firm j obtains by increasing its duopoly output given that its rival k produces the socially optimal output[10] $x^{K,E}_{k,SO}$. In addition, fee $t^{K,E}_2$ is decreasing in the incumbent's costs.[11]

First period. The regulator seeks to modify first-period output q in order to maximize social welfare. Specifically, this occurs when the socially optimal output under monopoly q^K_{SO} solves $MB^{K,NE}(q) = MD^{NE}(q)$. Analogous to the no-entry case, the emission fee $t^K_1 = MP^K_{inc}\left(q^K_{SO}\right)$ induces the monopolist to produce q^K_{SO}, where $q^K_{SO} = x^{K,NE}_{SO}$. Consequently, this fee coincides with that under monopoly in the second period, $t^K_1 = t^{K,NE}_2$. The following lemma summarizes output and emission fees in the subgame perfect equilibrium of the game. (For a parametric example, see subsection 2.3 below).

Lemma 1 (Flexible policy). *In the first period, the regulator sets an emission fee t^K_1, and the incumbent responds with a production function $q^K(t_1)$ which, in equilibrium, induces an output level $q^K(t^K_1) = q^K_{SO}$. Entry only ensues when the incumbent's costs are high. In the second period, if entry does not occur (NE), the regulator maintains fees at $t^{K,NE}_2 = t^K_1$, and the incumbent responds with an output function $x^{K,NE}_{inc}(t_2)$ which coincides with $q^K(t_1)$. If entry ensues (E), the regulator sets a second-period fee $t^{H,E}_2$ and $t^{L,E}_2$ when the incumbent's costs are high and low, respectively, and firms respond producing $x^{K,E}_i(t_2)$ where $i = \{inc, ent\}$ and $j \neq i$.*

[8] The proof of Lemma 1 shows that such an emission fee exists both under entry and no entry.

[9] Socially optimal output X must be produced by the most efficient firm. When the incumbent's costs are low, all output is produced by this firm, whereas when they are high, incumbent and entrant are equally efficient and hence output X can be split among them.

[10] This implies that, in order to find fee $t^{K,E}_2$ and individual output levels $x^{K,E}_{j,SO}$ and $x^{K,E}_{k,SO}$, the social planner must simultaneously solve $t^{K,E}_2 = MP^{K,E}_j\left(x^{K,E}_{j,SO}|x^{K,E}_{k,SO}\right)$ for both firms $j = \{inc, ent\}$ and $x^{K,E}_{j,SO} + x^{K,E}_{k,SO} = X^{K,E}_{SO}$.

[11] This is due to the fact that both firms respond less than proportionally to a given reduction in their rival's output decision, i.e., best response functions have a slope larger than -1; see proof of lemma 1.

2.2 Complete information under inflexible policy

We consider an additional benchmark where the regulator is unable to modify his tax policy between periods. This case illustrates institutional settings where the environmental policy is inflexible across time. First, in the case of no entry, the regulator seeks to induce the same optimal output in both periods, namely, q_{SO}^{K} and $x_{SO}^{K,NE}$. This can be achieved by a fee $t^{K,NE} = MP_{inc}^{K}\left(q_{SO}^{K}\right)$, which coincides with the optimal fee $t_1^K = t_2^{K,NE}$ under a flexible policy. If entry occurs, however, the regulator needs to set different fees to the first-period monopolist than to the second-period duopolists in order to induce the same socially optimal aggregate output. Any fixed fee t therefore produces a deadweight loss in one or both periods. Hence, in this setting the regulator minimizes the discounted sum of the absolute value of deadweight losses across both periods, choosing a fee t that solves

$$\min_{t} \ |DWL_1(t)| + \delta_R \, |DWL_2(t)| \tag{4}$$

where $\delta_R \in [0,1]$ denotes the regulator's discount factor. The deadweight loss of tax t in the first period is $DWL_1(t) \equiv \int_{q^K(t)}^{q_{SO}^K} \left[MB^{K,NE}(q) - MD^{NE}(q)\right] dq$, 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. Figure 1a below illustrates the first-period welfare loss of setting a fee t above the socially optimal fee t_1^K. In particular, fee t leads to a monopoly output $q^K(t)$ that lies below the socially optimal output q_{SO}^K.[12]

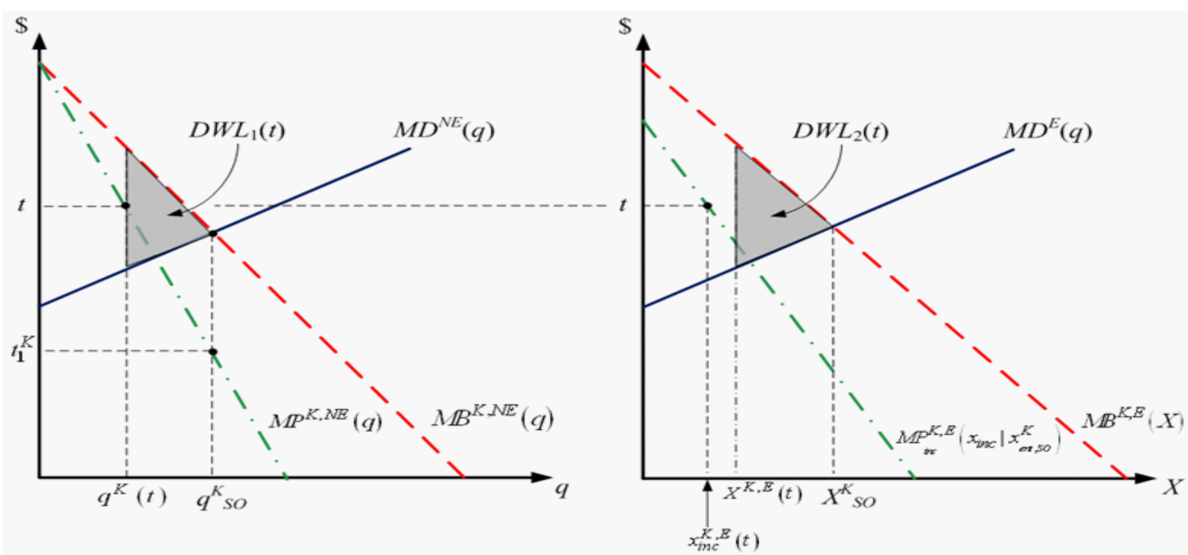

Figure 1a

Figure 1b

Similarly, the deadweight loss associated with tax t in the second period is given by $DWL_2(t) \equiv$

[12] In order to allow for the case where $t < t_1^K$, expression (4) considers the absolute value of the deadweight loss of fee t.

$\int_{X^{K,E}(t)}^{X_{SO}^K} \left[MB^{K,E}(X) - MD^E(X)\right] dX$, 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. Specifically, the constant fee t maps into $MP_j^{K,E}(\cdot)$, inducing firm j to produce $x_j^{K,E}(t)$. However, $DWL_2(t)$ is calculated from aggregate output $X^{K,E}(t)$. The following lemma summarizes equilibrium output and emission fees under an inflexible policy.

Lemma 2 (Inflexible policy). *When the incumbent's costs are low, the regulator commits to an emission fee $t^{L,NE}$ since entry does not ensue (NE), where $t^{L,NE} = t_1^L$, and the incumbent responds with a first-period output function $q^L(t)$ and with a second-period production function $x_{inc}^{L,NE}(t_2)$, which coincides with $q^L(t_1)$. When the incumbent's costs are high, the regulator commits to a fee $t^{H,E}$ since entry ensues (E), where $t^{H,E}$ solves (4), the incumbent responds with a first-period output function $q^H(t)$ and firms produce according to $x_i^{H,E}(t)$ where $i = \{inc, ent\}$ and $j \neq i$.*

In order to illustrate our results, we develop the following example throughout the paper (for more details, see Appendix 1).

2.3 Example

Flexible policy. Consider an inverse demand function $p(X) = 1 - X$ and incumbent costs $1 > c_{inc}^H = c_{ent} > c_{inc}^L$. Environmental damage is given by $d(X) = d \times X^2$ where $d \in \left[\frac{1}{2}, 1\right]$.[13] The socially optimal output that solves $MB^{K,NE}(x_{inc}) = MD^{NE}(x_{inc})$ is $q_{SO}^K = \frac{1-c_{inc}^K}{1+2d}$ and $q_{SO}^K = X_{SO}^K$, where $K = \{H, L\}$. As a consequence, the emission fee that induces q_{SO}^K in the first period is $t_1^K = (2d-1)q_{SO}^K$. The optimal second-period fee when the incumbent's costs are high is $t_2^{H,E} = (4d-1)\frac{X_{SO}^H}{2}$ under entry and $t_2^{H,NE} = t_1^H$ under no entry. Note that $t_2^{H,E} > t_1^H$, illustrating that the regulator sets more stringent fees to the duopolists than to the monopolist; as in Buchanan (1969). If, despite the incumbent's costs being low, entry occurs, the second-period fee is $t_2^{L,E} = \frac{A(1-c_{inc}^H)-B(1-c_{inc}^L)}{2A}$, where $A \equiv 1+2d$ and $B \equiv 2-2d$. This fee and the resulting duopoly output for both firms are positive as long as firms' costs are not extremely different, i.e., $c_{inc}^L < c_{inc}^H < \frac{1+2dc_{inc}^L}{A}$. Similarly as under high costs, optimal emission fees satisfy $t_2^{L,E} > t_1^L$. Finally, note that optimal fees with and without entry are increasing in d for all $K = \{H, L\}$.

Inflexible policy. Continuing with our example, and considering $\delta_R = 1$, the optimal tax t that the regulator chooses across both periods is $t^{K,NE} = (2d-1)q_{SO}^K$ if entry does not occur. In this case, the welfare-maximizing emission fee coincides with that under a flexible policy, $t^{K,NE} = t_1^K = t_2^{K,NE}$. The regulator has no incentive to revise the environmental policy because a monopoly is regulated at each stage. In contrast, when entry occurs the optimal tax is a weighted average of

[13] If instead, the environmental damage is extremely low (high), the regulator would choose to not reduce output levels setting a zero fee (reduce output to zero by setting a high fee, respectively).

first- and second-period taxes,[14] $t^{H,E} = \frac{9}{25}t_1^H + \frac{16}{25}t_2^{H,E}$, and thus $t_1^H < t^{H,E} < t_2^{H,E}$.

3 Signaling under a flexible policy

In this section we investigate the case where the incumbent and regulator are privately informed about the incumbent's marginal costs. This information setting describes cases where the social planner has accumulated relatively accurate information about the incumbent's cost structure over time. The entrant, however, bases his entry decision on the observed first-period output and 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 a first-period environmental tax t_1 on the incumbent's output and the incumbent chooses her first-period output level, $q(t_1)$.

3. Observing the first-period tax t_1 and the incumbent's output level $q(t_1)$, the entrant forms beliefs about the incumbent's marginal costs. Let $\mu(c_{inc}^H | q(t_1), t_1)$ 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.

5. If entry does not occur, the regulator imposes a second-period tax, $t_2^{K,NE}$, and the incumbent responds by producing a monopoly output $x_{inc}^{K,NE}(t_2^{K,NE})$. If, in contrast, entry ensues, the entrant observes the incumbent's costs and the regulator imposes a second-period tax $t_2^{K,E}$. Both firms then compete as Cournot duopolists, producing $x_{inc}^{K,E}(t_2^{K,E})$ and $x_{ent}^{K,E}(t_2^{K,E})$.

Step 5, therefore, implies that information is revealed after entry and all agents behave as under complete information. Hence, we hereafter focus on the informative role of first-period actions, as described in steps 1-4. For compactness, let D_{ent}^K denote the entrant's duopoly profits in equilibrium under a tax $t_2^{K,E}$ when the entrant faces a K-type incumbent. To make the entry decision interesting, assume that when the incumbent's costs are low, entry is unprofitable, whereas when they are high entry is profitable, i.e., $D_{ent}^L < F < D_{ent}^H$, where F denotes the fixed entry cost. 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 first-period profit-maximizing output, $q^H(t_1)$,

[14] Note that, as the regulator's discount factor approaches zero, the weight on t_1^H increases and that on $t_2^{H,E}$ decreases. Intuitively, the social planner assigns no value to the future deadweight loss and therefore selects a fee that minimizes deadweight loss in the first period of the game.

for any first-period tax t_1. She chooses $q^H(t_1)$ rather than deviating towards $q^A(t_1)$, where $q^A(t_1)$ exceeds the low-cost incumbent's first-period output under complete information, $q^L(t_1)$, if

$$M_{inc}^H(q^H(t_1), t_1) + \delta D_{inc}^H \geq M_{inc}^H(q^A(t_1), t_1) + \delta \overline{M}_{inc}^H, \tag{C1}$$

where $\delta \in [0, 1]$ represents the firm's discount factor, $M_{inc}^H(q(t_1), t_1)$ denotes the incumbent's first-period monopoly profits for any output function $q(t_1)$ and fee t_1, D_{inc}^H is the incumbent's duopoly profits evaluated at the equilibrium fee $t_2^{H,E}$ and $\overline{M}_{inc}^H$ represents her second-period monopoly profits at the equilibrium fee $t_2^{H,NE}$. The low-cost incumbent chooses $q^A(t_1)$ over $q^L(t_1)$ if

$$M_{inc}^L(q^A(t_1), t_1) + \delta \overline{M}_{inc}^L \geq M_{inc}^L(q^L(t_1), t_1) + \delta D_{inc}^L. \tag{C2}$$

Thus, conditions C1-C2 guarantee that the high-cost incumbent does not have incentives to mimic $q^A(t_1)$. The following subsection focuses on strategy profiles where information about the incumbent's costs is conveyed to the entrant (referred as "informative" equilibria) and afterwards analyzes those profiles where the entrant cannot infer the incumbent's type after observing the regulator's and incumbent's choices (i.e., "uninformative" equilibria).

3.1 Informative equilibrium

The entrant can infer accurate information about the incumbent's type when either: (1) the regulator chooses a type-dependent tax level[15] 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.[16] The following proposition demonstrates that only the third type of informative equilibrium can be supported as a Perfect Bayesian Equilibrium (PBE), and only the least-costly separating equilibrium survives the Cho and Kreps' (1987) Intuitive Criterion.

Proposition 1. *An informative equilibrium can be sustained when priors satisfy* $p > \overline{p} \equiv \frac{F - D_{ent}^L}{D_{ent}^H - D_{ent}^L}$*, where the regulator selects type-dependent emission fees* (t_1^H, t_1^A) *and the incumbent chooses output function* $q^H(t_1)$ *and* $q^A(t_1)$ *when her costs are high and low, respectively. The entrant responds staying out after observing output level* $q^A(t_1^A)$*, but enters otherwise. Output function* $q^A(t_1)$ *solves condition C1 with equality and* $q^A(t_1) > q^L(t_1)$*, and emission fee* t_1^A *induces the socially optimal output* q_{SO}^L *by solving* $q_{SO}^L = q^A(t_1)$*. However, strategy profiles where only one of the informed players (regulator or incumbent) uses a type-dependent first-period action cannot be sustained as a PBE.*

The low-cost incumbent hence selects an output function $q^A(t_1)$ higher than under complete

[15] 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.

[16] 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.

information, $q^L(t_1)$, in order to reveal her type to the entrant, thus deterring entry. The regulator, anticipating such higher production schedule, designs emission fee t_1^A in order to induce the socially optimal output q_{SO}^L by solving $q_{SO}^L = q^A(t_1)$. Therefore, the efficient output level —sustained under complete information settings with fee t_1^L— can also be induced in the informative equilibrium by fee t_1^A. Nonetheless, the monopolist's overproduction, i.e., $q^A(t_1) > q^L(t_1)$, implies that fee t_1^A, which induces the socially optimal output q_{SO}^L, must be more stringent than that under complete information, i.e., $t_1^A > t_1^L$. (Subsection 3.3 below elaborates on the welfare properties of this result).

This informative equilibrium can be sustained if the entrant observes "consistent" signals from both informed players. That is, after observing an equilibrium fee t_1^A, the entrant confirms that the incumbent's type must be low if, in addition, he observes an output level $q^A(t_1^A)$. If, instead, the output does not coincide with $q^A(t_1^A)$, the information conveyed in emission fee t_1^A is "inconsistent" with the output choice, and the entrant believes that the incumbent's costs must be high, attracting him to enter. A similar argument holds for fee t_1^H and output level $q^H(t_1^H)$. For the high-cost incumbent, these beliefs imply that, after emission fee t_1^H, she cannot deter entry by deviating to an output function $q(t_1^H) \neq q^H(t_1^H)$. For the low-cost incumbent, in contrast, these beliefs entail that, after the equilibrium fee t_1^A, she must "confirm" her type selecting output $q^A(t_1^A)$ if she seeks to deter entry.[17]

If the regulator sets an off-the-equilibrium fee t_1' the tax policy alone does not convey information, and thus the entrant only relies on the incumbent's output level to infer her type. Specifically, after observing fee t_1', the entrant can check if the observed output level coincides with $q^H(t_1')$, inducing him to enter, or with $q^A(t_1')$, deterring him from the market. Hence, the regulator facing a high-cost incumbent cannot deter entry by deviating from his equilibrium fee t_1^H. A similar argument applies to the regulator facing a low-cost firm, who can deter entry by inducing the socially optimal output q_{SO}^L, i.e., setting a fee t_1^A that solves $q_{SO}^L = q^A(t_1)$. Our result also implies that strategy profiles where only one of the informed agents, either the regulator or the incumbent, chooses a type-dependent strategy cannot be sustained as equilibria of the signaling game.[18]

Example. For the parametric example developed throughout the paper, the low-cost incumbent selects $q^A(t_1) = \frac{\left(1-c_{inc}^H\right)\left[A+\sqrt{3}\sqrt{\delta}\right]}{2A} - \frac{t_1}{2}$ in the informative equilibrium but chooses $q^L(t_1) = \frac{1-c_{inc}^L}{2} - \frac{t_1}{2}$ in the complete information setting; as the figure below illustrates.

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

[18] First, if the incumbent selects a type-independent output function $q(t_1)$, information is revealed by the type-dependent emission fees, leading the entrant to enter after observing t_1^H and $q(t_1^H)$, but stay out after t_1^A and $q(t_1^A)$. A type-independent output function $q(t_1)$, however, cannot be sustained in equilibrium since the high-cost incumbent, conditional on entry, obtains a larger profit deviating to $q^H(t_1)$. Second, if the regulator selects a type-independent fee t_1, the entrant only relies on the incumbent's output choice in order to infer her type, entering after observing t_1 and $q^H(t_1)$, but staying out after t_1 and $q^A(t_1)$. Conditional on entry, however, the regulator facing a high-cost incumbent has incentives to deviate towards t_1^H.

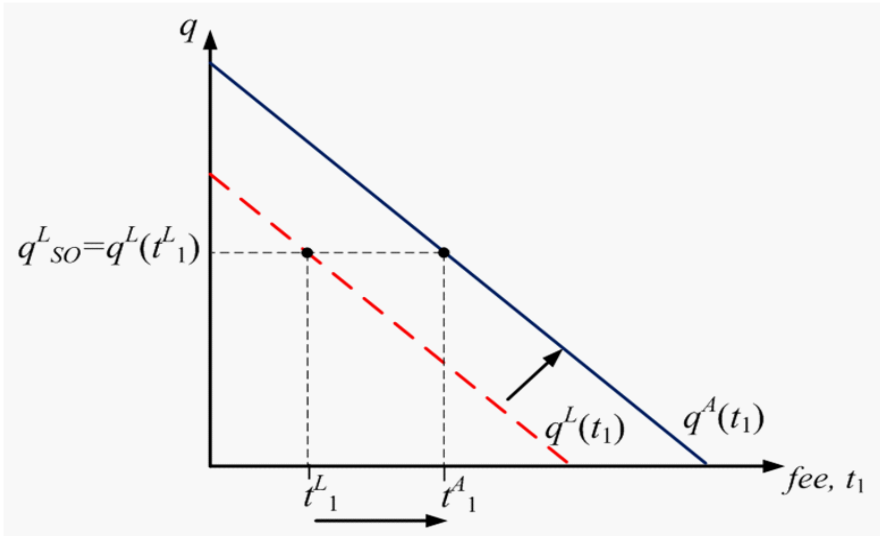

Fig 2. Informative PBE under flexible policy.

Hence, this firm's "separating effort," measured by the distance $q^A(t_1) - q^L(t_1)$, is positive if costs satisfy $c^H_{inc} < \frac{\sqrt{3}\sqrt{\delta}+Ac^L_{inc}}{\sqrt{3}\sqrt{\delta}+A}$. Intuitively, the low-cost incumbent finds profitable to separate in order to deter entry only if the potential entrant is relatively efficient, i.e., competition in the post-entry game would be "tough." Furthermore, the difference $q^A(t_1) - q^L(t_1)$ is decreasing in the environmental damage d. In particular, a given increase in d produces a larger increase in emission fees under monopoly than under duopoly, yielding a more significant reduction in monopoly profits. Hence, the low-cost incumbent's entry-deterrence benefits —understood as the difference between her second-period equilibrium profits under monopoly and duopoly— also decrease in d, ultimately reducing her incentives to separate. Finally, note that the regulator anticipates a higher production schedule $q^A(t_1)$, and designs an emission fee $t^A_1 = \frac{(1-c^H_{inc})[A+\sqrt{3}\sqrt{\delta}]-2(1-c^L_{inc})}{A}$ that solves $q^L_{SO} = q^A(t_1)$. As the figure above illustrates, fee t^A_1 still induces the monopolist to produce the socially optimal output q^L_{SO}, and it is higher than that under complete information, t^L_1, as long as the separating effort is positive.

3.2 Uninformative equilibrium

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

Proposition 2. *An uninformative equilibrium can be sustained when priors satisfy $p \leq \overline{p}$ in which the regulator selects a type-independent emission fee t^L_1 if overall social welfare satisfies $SW^{H,NE}(t^L_1, t^{H,NE}_2) \geq SW^{H,E}(t^H_1, t^{H,E}_2)$, and both types of incumbent choose output function $q^L(t_1)$, where t^L_1 and $q^L(t_1)$ coincide with those under complete information, if condition C4 holds.*

In order to mimic the low-cost incumbent, the high-cost firm selects output function $q^L(t_1)$. Since, in addition, the regulator chooses a type-independent emission fee t_1^L, 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 from the entrant and protect the market from entry. Specifically, the regulator sets a tax t_1^L above that under complete information, t_1^H. This "over-taxation" produces a loss in social welfare during the first period but a gain in the second period due to no entry. In particular, the welfare gain from deterring entry can be rationalized as follows. The regulator designs second-period emission fees to entail the same socially optimal output with and without entry. However, when entry is deterred, social welfare is larger given the savings in the fixed entry cost F. When this second-period welfare gain outweighs the first-period welfare loss from overtaxation, overall welfare increases, which occurs when entry costs are sufficiently high.

Intuitively, this suggests that in the uninformative equilibrium both informed agents must share the burden of concealing information from the entrant thus deterring 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, 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 priors. Therefore, it is not sufficient for one of the informed agents to be willing to practice such entry-deterrence strategy, suggesting that information is difficult to conceal when the actions of two different agents can serve as informative signals.

Example. Continuing with our above example, the regulator in this setting "over-taxes" the high-cost incumbent in order to conceal information from the entrant by setting a fee t_1^L which exceeds that under complete information t_1^H. In addition, a given increase in d produces a larger increase in t_1^L than in t_1^H, thereby enlarging the wedge $t_1^L - t_1^H = \frac{(2d-1)(c_{inc}^H - c_{inc}^L)}{A}$, and the associated first-period welfare loss from over-taxation. Hence, the regulator chooses a fee t_1^L when the gain in second-period social welfare due to no entry offsets the first-period loss from over-taxation. This condition holds when the welfare difference $SW^{H,NE}(t_1^L, t_2^{H,NE}) - SW^{H,E}(t_1^H, t_2^{H,E})$ is positive, which is satisfied when $d > d_{Flex}$, where $d_{Flex} \equiv \frac{-1}{2} + \frac{\left(c_{inc}^H - c_{inc}^L\right)^2}{4\delta F}$. For instance, when $\delta_R = \delta = 1$, $c_{inc}^H = \frac{1}{3}$ and $c_{inc}^L = \frac{1}{4}$,[19] $SW^{H,NE}(t_1^L, t_2^{H,NE}) \geq SW^{H,E}(t_1^H, t_2^{H,E})$ holds for all values of d, since $d_{Flex} = -0.15$.

In addition, the high-cost incumbent selects output level $q^L(t_1^L)$ in order to conceal her type and deter entry. In particular, she overproduces relative to her equilibrium output under complete information, $q^H(t_1^H)$, thereby exerting a "pooling effort" of $q^L(t_1^L) - q^H(t_1^H) = \frac{c_{inc}^H - c_{inc}^H}{A}$, which is

[19] In addition, we consider entry costs of $F = 0.005$. Other parameter combinations yield similar results, as long as F satisfies $D_{ent}^L < F < D_{ent}^H$.

positive and decreasing in the environmental damage d. That is, a more polluting output reduces the firm's incentives to deter entry. As described above, firms' entry-deterrence benefits are decreasing in d, reflecting that the high-cost incumbent's incentives to overproduce —in order to deter entry— diminish in d.

3.3 Welfare comparisons

Let us next investigate the conditions under which equilibrium welfare under incomplete information is larger than in complete information contexts.

Corollary 1. *Under a flexible policy, social welfare in the informative equilibrium coincides with that under complete information settings, for all parameter conditions. In addition, social welfare in the uninformative equilibrium exceeds that under complete information.*

The informative equilibrium produces the same social welfare as under complete information.[20] In particular, the regulator induces the same first-period socially optimal output q_{SO}^L in both information contexts, thus yielding the same welfare in both settings. Importantly, our results differ from those in standard entry-deterrence models in which the regulator is absent, where social welfare can increase if the welfare gain from a higher first-period production offsets the incumbent's profit loss from exerting her separating effort. Indeed, in our model such welfare gain is absent, given that the regulator induces the socially optimal output in both information contexts, thus suggesting that the introduction of incomplete information does not affect social welfare. This result does not imply that the presence of the regulator is welfare neutral. In contrast, the regulator's ability to induce socially optimal output during both periods has a positive effect on welfare, relative to entry-deterrence games where he is absent. Social welfare in the uninformative equilibrium $SW^{H,NE}(t_1^L, t_2^{H,NE})$, in contrast, is unambiguously larger than that under complete information $SW^{H,E}(t_1^H, t_2^{H,E})$ since, from our previous discussion, $SW^{H,NE}(t_1^L, t_2^{H,NE}) \geq SW^{H,E}(t_1^H, t_2^{H,E})$ holds by definition.

4 Signaling under an inflexible policy

In this section we examine the signaling role of emission fees and output when the regulator must commit to a single tax t. The time structure of the game coincides with that in the previous section, except for step 5, since now the regulator does not have the option to revise his environmental policy. To make entry decision interesting, we consider that when the incumbent's costs are low, entry is unprofitable, i.e., the entrant's duopoly profits, $D_{ent}^L(t)$, lie below his fixed entry cost F, $D_{ent}^L(t) < F$, for any emission fee t. Hence, when emission fees are absent, the entrant stays out, i.e., $D_{ent}^L(0) < F$. In contrast, when the incumbent's costs are high, entry is profitable under the

[20] We focus on the welfare comparison for the first period alone, since second-period equilibrium fees and output are equal in both information settings. Similarly, we only consider the low-cost incumbent, given that the high-cost incumbent's output (and the fees the regulator sets to this firm) coincide in the informative equilibrium and under complete information.

inflexible fee $t^{H,E}$, i.e., $D^H_{ent}(t^{H,E}) > F$. The following propositions describe the informative and uninformative equilibria that survive the Cho and Kreps' (1987) Intuitive Criterion.

Proposition 3. *Under an inflexible policy, only an informative equilibrium can be sustained when priors satisfy* $p > \overline{p}\left(t^{L,NE}\right) \equiv \frac{F-D^L_{ent}\left(t^{L,NE}\right)}{D^H_{ent}(t^{L,NE})-D^L_{ent}(t^{L,NE})}$*, where the regulator selects type-dependent emission fees* $(t^{H,E}, \widetilde{t}^A)$ *and the incumbent chooses output function* $q^H(t)$ *when her costs are high and* $\widetilde{q}^A(t)$ *when her costs are low, respectively. The entrant responds staying out after observing fee* $\widetilde{t}^A$ *and output level* $\widetilde{q}^A(\widetilde{t}^A)$*, but enters otherwise. Output function* $\widetilde{q}^A(t)$ *satisfies* $\widetilde{q}^A(t) > q^L(t)$*, and emission fee* $\widetilde{t}^A$ *solves*

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

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

This result shares similarities with that in Proposition 1 for a flexible policy. In particular, the low-cost incumbent increases his output function relative to complete information, from $q^L(t)$ to $\widetilde{q}^A(t)$, in order to convey her type to potential entrants, thus deterring entry, and the regulator anticipates such higher production schedule. Unlike the informative equilibrium under a flexible policy, however, he cannot design emission fees that exactly induce the socially optimal output q^L_{SO}. Indeed, under an inflexible policy, he must select a constant fee $\widetilde{t}^A$ that takes into account that the incumbent uses a different output function in the first and second period, $\widetilde{q}^A(t)$ and $x^{L,NE}_{inc}(t)$, respectively, where $x^{L,NE}_{inc}(t) = q^L(t)$. Therefore, setting a constant fee across time must produce inefficiencies in either one or both periods. The regulator hence selects an emission fee that minimizes the deadweight loss resulting from such inflexible fee.

In addition, note that the probability cutoff that attracts entry in the informative equilibrium is lower than under a flexible policy, i.e., $\overline{p}(t^{L,NE}) < \overline{p}$, which is explained by the entrant's duopoly profits under each type of policy.[21] Intuitively, under an inflexible emission fee the entrant only faces the risk of dealing with a low-cost incumbent, given that fee $t^{L,NE}$ remains constant in the post-entry game. Under a flexible policy, however, the entrant must deal with an additional source of uncertainty: if he competes against a high-cost (low-cost) incumbent the regulator revises his policy to the more stringent fee $t^{H,E}_2$ ($t^{L,E}_2$), further reducing the entrant's expected profits. Therefore, entering becomes attractive under a larger set of priors when the policy is inflexible, and the informative equilibrium can be sustained under a larger set of parameter conditions.

[21] For compactness, probability cutoff under flexible policies is denoted as $\overline{p}$. It is important to note, however, that such cutoff is a function of the entrant's profits when dealing with a high- and low-cost incumbent and, as a consequence, depends on second-period fees $t^{H,E}_2$ and $t^{L,E}_2$. In the case of inflexible policies, probability cutoff $\overline{p}(t^{L,NE})$ is also a function of the entrant's profits, but they depend on the constant fee $t^{L,NE}$, both when the incumbent's costs are high and low.

Proposition 4. *Under an inflexible policy, an uninformative equilibrium where the regulator commits to a type-independent emission fee* $t^{L,NE}$*, both types of incumbent choose output function* $q^L(t)$*, and entry does not ensue can be sustained when priors satisfy* $p \leq \overline{p}\left(t^{L,NE}\right)$ *and social welfare satisfies* $SW^{H,NE}(t^{L,NE}) \geq SW^{H,E}(t^{H,E})$.

The high-cost incumbent hence mimics the output function of the low-cost firm, $q^L(t)$, in order to hide her type from the potential entrant. In addition, the regulator facilitates such concealment strategy by selecting an emission fee $t^{L,NE}$, which leads the potential entrant to stay out given his low priors, i.e., $p \leq \overline{p}\left(t^{L,NE}\right)$.

Let us describe the welfare implications of this equilibrium result, relative to complete information settings. Under complete information, entry ensues when the incumbent's costs are high, and therefore a constant emission fee $t^{H,E}$ induces inefficient output levels during both periods.[22] A similar argument is applicable under the uninformative equilibrium, where the regulator's choice of $t^{L,NE}$ cannot guarantee a socially optimal production either. Overall social welfare is hence suboptimal in both information contexts. However, fee $t^{L,NE}$ in the uninformative equilibrium yields a larger output than under complete information (and as a result welfare increases) if the environmental damage is sufficiently small. (Corollary 2 below identifies specific parameter conditions in the context of our parametric example).[23]

Example. For the sake of comparison, let us continue with our parametric example. The low-cost incumbent selects $\widetilde{q}^A(t) = \frac{(1-c^H_{inc}-t)(3+\sqrt{5}\sqrt{\delta})}{6}$ in the informative equilibrium but chooses $q^L(t) = \frac{1-c^H_{inc}}{2} - \frac{t}{2}$ in the complete information setting. Therefore, the separating effort $\widetilde{q}^A(\widetilde{t}^A) - q^L(t^{L,NE})$ is positive if costs satisfy $c^H_{inc} < \frac{(3\sqrt{5}-5)(1-c^L_{inc})+2Ac^L_{inc}}{2A}$, where $\delta_R = \delta = 1$. Similarly as in our example under a flexible policy, this result implies that the low-cost incumbent is only willing to exert separating effort when the potential entrant is a "tough" competitor. In addition, the separating effort is decreasing in the environmental damage, d, which can be rationalized through the incumbent's entry-deterrence benefits, as under a flexible policy. In the informative equilibrium, the regulator sets a fee $\widetilde{t}^A$ that minimizes the discounted sum of deadweight losses. For the case in which $c^H_{inc} = 1/4$ and $c^L_{inc} = 0$ this fee is $\widetilde{t}^A = \frac{39+9\sqrt{5}-[12(6+\sqrt{5})]A^{-1}}{2(23+6\sqrt{5})}$.

Let us now examine the uninformative equilibrium. In this setting, the regulator "over-taxes" the high-cost incumbent setting a fee $t^{L,NE}$, which exceeds that under complete information $t^{H,E}$, since $t^{L,NE} - t^{H,E} = \frac{(50d-17)c^H_{inc}+25(1-2d)c^L_{inc}-8}{25A}$ is positive for all $\frac{8+25(2d-1)c^L_{inc}}{8+25(2d-1)} < c^H_{inc} < \frac{1+2dc^L_{inc}}{A}$. In addition, a given increase in d produces a larger increase in $t^{L,NE}$ than in $t^{H,E}$, thereby enlarging the difference $t^{L,NE} - t^{H,E}$, and the associated first-period welfare loss from over-taxation. Finally, the high-cost incumbent overproduces selecting output level $q^L(t^{L,NE})$. Therefore, she exerts a

[22] In particular, under complete information, fee $t^{H,E}$ yields an output level above q^H_{SO}, which is socially optimal during the first-period game; whereas $t^{H,E}$ entails a lower output level than it would be efficient in the second-period game. For more details, see proof of Corollary 2.

[23] Alternatively, the regulator could set a sufficiently high fee $\bar{t}$ that blockades entry, i.e., $D^H_{ent}(t) \leq F$ for all $t \geq \bar{t}$, thus nullifying the informative role of the incumbent's first period output choice. Fee $\bar{t}$ is only applicable under inflexible policies since under no commitment fees can be modified after the first period, and thereby entry cannot be credibly blockaded. We focus, however, on emission fees that can communicate information to the entrant.

"pooling effort" of $q^L(t^{L,NE}) - q^H(t^{H,E}) = \frac{4+21c_{inc}^H - 25c_{inc}^L}{25A}$, which is positive and decreasing in the environmental damage d. That is, a more polluting output reduces the firm's incentives to deter entry. As described above for the informative equilibrium, firms' entry-deterrence benefits are decreasing in d, reflecting that the high-cost incumbent's incentives to overproduce diminish in d. Therefore, when environmental damage is relatively low, the incumbent bears most of the effort in deterring entry since her overproduction is significant while over-taxation is small. An opposite argument applies when the environmental damage is high.

4.1 Welfare comparisons

We next examine under which conditions an inflexible policy generates a larger social welfare under incomplete than complete information contexts.

Corollary 2. *Under an inflexible policy, social welfare in the informative equilibrium is weakly lower than under complete information, for all parameter values. Social welfare in the uninformative equilibrium is larger than under complete information only when the environmental damage, d, is sufficiently large. For our parametric example, this occurs when $d > d_{Inflex}$, where*

$$d_{Inflex} \equiv \frac{1}{2} + \frac{10F - \sqrt{100F^2 - (c_{inc}^H - c_{inc}^L)^2 L}}{5(c_{inc}^H - c_{inc}^L)^2}$$

where $L \equiv 25(c_{inc}^L)^2 + c_{inc}^H(2 - 50c_{inc}^L) + 24\left(c_{inc}^H\right)^2 - 100F - 1.$

Let us first examine the welfare properties of the informative equilibrium. The output level under this equilibrium, $\widetilde{q}^A(\widetilde{t}^A)$, exceeds that under complete information, $q^L(t^{L,NE})$, which is socially optimal since $q^L(t^{L,NE}) = q^L(t_1^L) = q_{SO}^L$. Therefore, the overproduction in the informative equilibrium of Proposition 3 entails a first-period 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 $q^L(t)$. Hence, the informative equilibrium fee $\widetilde{t}^A$ induces an output level $x_{inc}^{L,NE}(\widetilde{t}^A)$ below the socially optimum q_{SO}^L since $\widetilde{t}^A > t^{L,NE}$. Under complete information, in contrast, the inflexible fee $t^{L,NE}$ induces second-period output to become socially optimal, i.e., $x_{inc}^{L,NE}(t^{L,NE}) = q^L(t^{L,NE}) = q_{SO}^L$. Therefore, the introduction of incomplete information yields output inefficiencies during both time periods, thus reducing overall welfare. This result differs from that in flexible policy regimes, whereby incomplete information does not affect social welfare.

Let us now analyze the welfare properties of the uninformative equilibrium. As described in Proposition 4, production is neither socially optimal under the uninformative equilibrium nor the complete information setting, implying a sub-optimal social welfare in both information contexts. However, fee $t^{L,NE}$ in the uninformative equilibrium yields a larger welfare when environmental damage is sufficiently large, i.e., $d > d_{Inflex}$. Finally, cutoff d_{Inflex} satisfies $d_{Flex} < d_{Inflex}$ when firms are relatively asymmetric. In particular, the welfare loss from overtaxation increases in the cost differential among firms, thus inducing the regulator to behave as prescribed in the uninformative equilibrium under a larger set of parameter when he has the ability to redesign environmental policy in future periods than when he must commit to a constant emission fee.

4.2 Information transmission

Let us now evaluate how our equilibrium results with and without flexible policies perform in terms of information transmission. We develop our comparisons using the results from our previous example. In the informative equilibrium, we contrast the low-cost incumbent's separating effort when the environmental policy is inflexible across time, $\widetilde{q}^A(t^{L,NE}) - q^L(t^{L,NE})$, with that under a flexible policy, $q^A(t_1) - q^L(t_1)$. The next table illustrates that separating effort is smaller with an inflexible policy; a result which holds for several parameter values.[24] Given that under an inflexible policy the tax level is held fixed across time, the incumbent's entry-deterrence benefits only arise from her monopoly power. In contrast, the tax level under a flexible policy is higher under duopoly than under monopoly, producing a further reduction in duopoly profits. Consequently, the entry-deterrence benefits increase under a flexible policy, providing the high-cost incumbent with more incentives to conceal her type from the entrant by mimicking the low-cost firm's output choices. In order to avoid such a pooling outcome, the low-cost incumbent must increase the extent of her overproduction. Information transmission therefore becomes more costly under a flexible environmental policy.

			Separation	*Separation*	*Difference*
		(c_{inc}^H, c_{inc}^L)	*Inflexible policy*	*Flexible policy*	
$\delta = 1$	$d = 1$	$\left(\frac{1}{4}, 0\right)$	0.007	0.09	-0.083
		$\left(\frac{1}{2}, \frac{1}{3}\right)$	0.004	0.06	-0.056
	$d = \frac{1}{2}$	$\left(\frac{1}{4}, 0\right)$	0.038	0.20	-0.162
		$\left(\frac{1}{2}, \frac{1}{3}\right)$	0.025	0.13	-0.105
$\delta = \frac{3}{4}$	$d = 1$	$\left(\frac{1}{4}, 0\right)$	0.002	0.06	-0.058
		$\left(\frac{1}{2}, \frac{1}{3}\right)$	0.001	0.04	-0.039
	$d = \frac{1}{2}$	$\left(\frac{1}{4}, 0\right)$	0.025	0.16	-0.135
		$\left(\frac{1}{2}, \frac{1}{3}\right)$	0.017	0.10	-0.083

Table I. Separating effort in the informative equilibrium.

4.3 Discussion

Flexible vs. Inflexible policy. Our results under flexible policies describe countries with environmental protection agencies that rapidly adapt to changes in market conditions, such as the number of firms operating in an industry. They suggest that the regulator is more inclined to help the

[24] For compactness, we present our comparisons for eight different parameter combinations, all of them yielding less separating effort under an inflexible policy. Other parameter combinations produce similar results and can be provided by the authors upon request.

incumbent's efforts to deter entry when firms are relatively asymmetric in their cost structure. In contrast, institutions that do not frequently adjust their policies to changing industry conditions are less likely to facilitate the emergence of such entry-deterrence practices, thus revealing information to potential entrants under larger parameter conditions.

Regulator's role. Our results also identify a new role of emission fees often overlooked when evaluating environmental policy, namely, its ability to convey or conceal information to potential competitors, thus promoting or hindering entry. Specifically, in the uninformative equilibrium the regulator's practice of over-taxation helps the incumbent to 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.

5 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 the presence of the regulator facilitates information transmission. In addition, flexible policies promote the conveyance of information under larger parameter conditions than inflexible policies. Therefore, our results identify a potential benefit of flexible policies, namely, hampering 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 cannot choose whether to commit to a particular emission fee across time. 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.

6 Appendix

6.1 Appendix 1

Flexible policy. Given a second-period fee t_2, under no entry the K-type incumbent solves

$$\max_{x_{inc}} (1 - x_{inc})x_{inc} - \left(c_{inc}^K + t_2\right) x_{inc}$$

which yields an output function $x_{inc}^{K,NE}(t_2) = \frac{1-\left(c_{inc}^K+t_2\right)}{2}$. The social planner seeks to induce an output level that maximizes social welfare,

$$\max_{x_{inc}} CS(x_{inc}) + PS(x_{inc}) + T_2^{K,NE} - d \times (x_{inc})^2$$

where $CS(x_{inc}) \equiv \frac{1}{2}(x_{inc})^2$, $PS(x_{inc}) \equiv (1 - x_{inc})x_{inc} - \left(c_{inc}^K + t_2\right) x_{inc}$, denote consumer and producer surplus, respectively, and $T_2^{K,NE} \equiv t_2 x_{inc}$ represents tax revenue under no entry. Taking first-order conditions, we obtain the socially optimal output $x_{SO}^K = \frac{1-c_{inc}^K}{1+2d}$. Hence, the emission fee t_2 that induces the monopolist to produce x_{SO}^K is that solving $\frac{1-\left(c_{inc}^K+t_2\right)}{2} = \frac{1-c_{inc}^K}{1+2d}$, i.e., $t_2^{K,NE} = (2d-1)\frac{1-c_{inc}^K}{1+2d}$, or $t_2^{K,NE} = (2d-1)x_{SO}^K$ (A similar fee, $t_1^K = (2d-1)q_{SO}^K$, is implemented in the first period, since the incumbent is the unique firm operating in the market, where $x_{SO}^K = q_{SO}^K$)

In the case of entry, the incumbent (entrant) solves

$$\max_{x_{inc}} (1 - x_{inc} - x_{ent})x_{inc} - \left(c_{inc}^K + t_2\right) x_{inc} \quad \text{and} \quad \max_{x_{ent}} (1 - x_{ent} - x_{inc})x_{ent} - \left(c_{ent} + t_2\right) x_{ent} - F$$

respectively, yielding an output function $x_i^{K,E}(t_2) = \frac{1-2c_i^K+c_j^K-t_2}{3}$ for any firm $i = \{inc, ent\}$ where $j \neq i$. The social planner seeks to induce an output level that maximizes

$$\max_{X} CS(X) + PS(X) + T_2^K - d \times X^2$$

where $X \equiv x_{inc} + x_{ent}$, $CS(X) \equiv \frac{1}{2}(X)^2$, $PS(X) \equiv (1 - X)X - \left(c_{inc}^K + t_2\right) X - F$, and $T_2^K \equiv t_2 X$. Note that the producer surplus $PS(X)$ considers the incumbent's marginal costs. This is due to the fact that, in order to allocate the production decision of the socially optimal output, a benevolent social planner would produce using the most efficient firm. Specifically, when the incumbent's costs are low, all socially optimal output would be produced by this firm, whereas when they are high, incumbent and entrant are equally efficient, $c_{inc}^H = c_{ent}$, and hence the socially optimal output can be equally split among them. Taking first-order conditions, we obtain the aggregate socially optimal output $X_{SO}^K = \frac{1-c_{inc}^K}{1+2d}$, which coincides with x_{SO}^K. Finally, in order to find fee $t_2^{K,E}$ and individual output levels $x_{inc,SO}^{K,E}$ and $x_{ent,SO}^{K,E}$, the social planner must simultaneously solve

$$x_{inc,SO}^{K,E} + x_{ent,SO}^{K,E} = \frac{1 - c_{inc}^K}{1 + 2d} \tag{A.1}$$

(the sum of incumbent's and entrant's output coincides with the socially optimal output X_{SO}^{K}) and

$$x_{inc}^{K,E}(t_2) = \frac{1 - 2c_{inc}^{K} + c_{ent}^{K} - t_2}{3}, \text{ and} \tag{A.2}$$

$$x_{ent}^{K,E}(t_2) = \frac{1 - 2c_{ent}^{K} + c_{inc}^{K} - t_2}{3} \tag{A.3}$$

Simultaneously solving equations A.1-A.3 yields the emission fee $t_2^{H,E} = \frac{4d-1}{2}\frac{1-c_{inc}^{K}}{1+2d}$, or $t_2^{H,E} = (4d-1)\frac{X_{SO}^{H}}{2}$, when the incumbent's costs are high, which is strictly positive if $d > \frac{1}{4}$, a condition that holds given that $d > \frac{1}{2}$ by assumption. Substituting $t_2^{H,E}$ into the output function $x_i^{K,E}(t_2)$ yields $x_{inc}^{H,E}(t_2^{H,E}) = x_{ent}^{H,E}(t_2^{H,E}) = \frac{1}{2}\frac{1-c_{inc}^{H}}{1+2d} = \frac{X_{SO}^{H}}{2}$.

Simultaneously solving equations A.1-A.3 when the incumbent's costs are low, yields an emission fee $t_2^{L,E} = \frac{A(1-c_{inc}^{H})-B(1-c_{inc}^{L})}{2A}$, where $A \equiv 1+2d$ and $B \equiv 2-2d$. Hence, the equilibrium output levels evaluated at fee $t_2^{L,E}$ are

$$x_{inc}^{L,E}(t_2^{L,E}) = \frac{1 + Ac_{inc}^{H} - (2+2d)c_{inc}^{L}}{2A} \quad \text{and} \quad x_{ent}^{L,E}(t_2^{L,E}) = \frac{1 - Ac_{inc}^{H} + Bc_{inc}^{L}}{2A}$$

which are positive if, respectively, $c_{inc}^{H} > \frac{(2+2d)c_{inc}^{L}-1}{A}$ and $c_{inc}^{H} < \frac{1+2dc_{inc}^{L}}{A}$. In addition, the emission fee $t_2^{L,E}$ is positive if $c_{inc}^{H} < \frac{4d-1+Bc_{inc}^{L}}{A}$. Condition $c_{inc}^{H} > \frac{(2+2d)c_{inc}^{L}-1}{A}$, however, holds for all $c_{inc}^{H} > c_{inc}^{L}$ since it originates at the negative quadrant (when $c_{inc}^{L} = 0$, the cutoff originates at $-\frac{1}{A}$) and reaches $c_{inc}^{H} = 1$ when $c_{inc}^{L} = 1$. Therefore, $\frac{(2+2d)c_{inc}^{L}-1}{A} < c_{inc}^{L}$. Furthermore, condition $c_{inc}^{H} < \frac{1+2dc_{inc}^{L}}{A}$ is more restrictive than $c_{inc}^{H} < \frac{4d-1+Bc_{inc}^{L}}{A}$. Indeed, both cutoffs reach $c_{inc}^{H} = 1$ when $c_{inc}^{L} = 1$, but $\frac{1+2dc_{inc}^{L}}{A}$ originates at $\frac{1}{A}$ while $\frac{4d-1+Bc_{inc}^{L}}{A}$ originates at a higher vertical intercept $\frac{4d-1}{A}$, since $4d-1 > 1$ given that $d > \frac{1}{2}$. Therefore, only condition $c_{inc}^{H} < \frac{1+2dc_{inc}^{L}}{A}$ is binding and, in order to have a positive emission fee that induces positive output levels from both firms, we only need firms' costs to be relatively symmetric, i.e., $c_{inc}^{L} < c_{inc}^{H} < \frac{1+2dc_{inc}^{L}}{A}$.

Inflexible policy. 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 $t^{L,NE}$ that coincides with $t_1^{L} = (2d-1)q_{SO}^{K}$ under a flexible policy. 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 $q^{H}(t) = \frac{1-(c_{inc}^{H}+t)}{2}$. In addition, $MB^{H,NE}(q) = (1-q) - c_{inc}^{H}$, whereas $MD^{NE}(q) = 2dq$. Integrating, we obtain

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

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

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

where socially optimal output is still $X^H_{SO} = \frac{1-c^H_{inc}}{1+2d}$, and $X^{H,E}(t) = x^{H,E}_{inc}(t) + x^{H,E}_{ent}(t)$, where $x^{H,E}_{inc}(t) = x^{H,E}_{ent}(t) = \frac{1-\left(c^H_{inc}+t\right)}{3}$ 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 $c^H_{inc} = c_{ent}$, and both firms' production functions coincide.) Furthermore, $MB^{H,E}(X) = (1-X) - c^H_{inc}$, whereas $MD^{NE}(X) = 2dX$. Integrating, we obtain

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

The regulator can construct the discounted sum $DWL_1(t) + \delta_R DWL_2(t)$ (note that both $DWL_1(t)$ and $DWL_2(t)$ are strictly positive) and take first-order conditions with respect to t, obtaining $t^{H,E} = \frac{(1-c^H_{inc})[8\delta_R 2dG - G]}{AG}$ where $G \equiv 9 + 16\delta_R$. In the specific case where the regulator does not discount future payoffs, $\delta_R = 1$, fee $t^{H,E}$ becomes $t^{H,E} = \frac{(1-c^H_{inc})[50d-17]}{25A}$. Note that the emission fee $t^{H,E}$ yields the minimum of the objective function $DWL_1(t) + \delta_R DWL_2(t)$ since such objective function is convex in t, i.e., $\frac{\partial^2[DWL_1(t)+\delta_R DWL_2(t)]}{\partial t^2} = \frac{AG}{36} > 0$ for all parameter values.

Finally, fee $t^{H,E}$ can be expressed as a linear combination of the equilibrium fees under a flexible policy, t^H_1 and $t^{H,E}_2$, by solving $t^{H,E} = \alpha t^H_1 + (1-\alpha)t^{H,E}_2$, where parameter α describes the relative weight on first-period taxes. For the case in which $\delta_R = 1$, parameter $\alpha = \frac{9}{25}$. Hence, $t^{H,E} = \frac{9}{25}t^H_1 + \frac{16}{25}t^{H,E}_2$, and thus $t^H_1 < t^{H,E} < t^{H,E}_2$. From our analysis of the flexible policy, we know that fee $t^{H,E}_2$ is positive and induces positive output levels from both firms in the industry. Therefore, a lower fee $t^{H,E}$ in the inflexible policy regime must also induce positive production levels from both incumbent and entrant. ■

6.2 *Proof of Lemma 1*

Second period, No entry. The socially optimal output under monopoly $x^{K,NE}_{SO}$ solves $MB^{K,NE}(x) = MD^{NE}(x)$, where

$$MB^{K,NE}(x) \equiv \frac{\partial[CS + \pi^{K,NE}_{inc} + T^{K,NE}_2]}{\partial x} = p(x) - c^K_{inc}$$

and $MD^{NE}(x) \equiv d'(x)$. Socially optimal output under monopoly $x^{K,NE}_{SO}$ exists if $MB^{K,NE}(0) > MD^{NE}(0)$, which holds since $p(0) - c^K_{inc} > d'(0)$. The emission fee that induces the monopolist to produce $x^{K,NE}_{SO}$ is $t^{K,NE}_2 = MP^{K,NE}_{inc}\left(x^{K,NE}_{SO}\right)$, where $MP^{K,NE}_{inc}(x_{inc}) \equiv \frac{\partial \pi^{K,NE}_{inc}(x_{inc})}{\partial x_{inc}}$. Note that

$t_2^{K,NE}$ is decreasing in costs. In particular, an increase in costs shifts the $MP_{inc}^{K,NE}(x_{inc})$ function downwards, decreasing the value of $x_{SO}^{K,NE}$ that solves $MB^{K,NE}(x) = MD^{NE}(x)$. Given that $MD^{NE}(x)$ is unaffected by the change in costs and it is increasing in x, the optimal value of $t_2^{K,NE}$ decreases.

Second period, Entry. The socially optimal aggregate output under duopoly $X_{SO}^{K,E}$ solves $MB^{K,E}(X) = MD^{E}(X)$, where

$$MB^{K,E}(X) \equiv p(X) - c_{inc}^{K}$$

and $MD^{E}(X) \equiv d'(X)$ where $X = x_{inc} + x_{ent}$. In addition, $MB^{K,E}(X)$ is decreasing in X and $MD^{E}(X)$ is increasing in X since its slope is $d''(X) > 0$. Optimal aggregate output under duopoly $X_{SO}^{K,E}$ exists if $MB^{K,E}(0) > MD^{E}(0)$, which holds since $p(0) - c_{inc}^{K} > d'(0)$. The emission fee $t_2^{K,E}$ that induces the aggregate output $X_{SO}^{K,E}$ is $t_2^{K,E} = MP_j^{K,E}\left(x_{j,SO}^{K,E} | x_{k,SO}^{K,E}\right)$ for all $j = \{inc, ent\}$ and $k \neq j$, where $MP_j^{K,E}\left(x_j | x_{k,SO}^{K,E}\right) \equiv \frac{\partial \pi_j^{K,E}(x_j | x_{k,SO}^{K,E})}{\partial x_j}$ for all firm $j \neq k$. Note that $t_2^{K,E}$ is decreasing in the incumbent's costs, i.e., $t_2^{L,E} > t_2^{H,E}$. In particular, an increase in the incumbent's costs decreases $X_{SO}^{K,E}$ since both firms' best response functions have a slope larger than -1. That is,

$$\frac{\partial x_{ent}(x_{inc})}{\partial x_{inc}} = -\frac{\frac{\partial^2 \pi_{ent}^{K,d}}{\partial x_{ent} \partial x_{inc}}}{\frac{\partial^2 \pi_{ent}^{K,d}}{\partial x_{ent}^2}} = -\frac{p' + p'' x_{ent}}{2p' + p'' x_{ent}} > -1$$

where $p \equiv p(X)$ and $p'' = 0$ given that demand is linear. Given that $MD^{E}(X)$ is unaffected by the change in costs and it is increasing in X, the optimal value of $t_2^{K,E}$ decreases.

First period. First, note that first-period actions (output level q and emission fee t_1) do not affect second-period payoffs, i.e., second-period profits and welfare are independent of q and t_1. First-period actions do not affect the entrant's decision either, since the perfectly-informed entrant only enters when the incumbent's costs are high. The socially optimal output under first-period monopoly q_{SO}^{K} solves $MB^{K,NE}(q) = MD^{NE}(q)$, where

$$MB^{K,NE}(q) \equiv p(q) - c_{inc}^{K}$$

and $MD^{NE}(q) \equiv d'(q)$. By a similar argument as for $t_2^{K,E}$ emission fee t_1^{K} exists and is decreasing in costs. ■

6.3 *Proof of Lemma 2*

When the incumbent's costs are low, entry does not ensue, and the regulator induces the same optimal output in both periods, namely, q_{SO}^{K} and $x_{SO}^{K,NE}$. This can be achieved by a fee $t^{K,NE} = MP_{inc}^{K}\left(q_{SO}^{K}\right)$, which coincides with the optimal fee $t_1^{K} = t_2^{K,NE}$ under a flexible policy. If the incumbent's costs are high, the entrant is attracted to the industry, and setting a constant fee t during both time periods produces a deadweight loss in one or both periods. Hence, in this setting the regulator chooses a fee t that solves

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

where $DWL_1(t)$ and $DWL_2(t)$ were described in the text. ■

6.4 *Proof of Proposition 1*

We next show that the only informative strategy profile that can be sustained in equilibrium has 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. Conversely, the strategy profile where only the regulator chooses a type-dependent strategy cannot be sustained as a PBE. We then show that only the least-costly type-dependent strategy profile survives the Cho and Kreps' (1987) Intuitive Criterion.

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 that the regulator chooses a type-independent first-period tax t_1' whereas the incumbent selects a type-dependent output function $q^H(t_1)$ when her costs are high, but chooses $q^{L,sep}(t_1)$ when her costs are low for any given tax t_1. [Note that the separating output function $q^{L,sep}(t_1)$ is weakly higher than the output function selected by the low-cost incumbent under complete information, $q^L(t_1)$. Otherwise, the high-cost incumbent could be tempted to pool with the low-cost incumbent by selecting $q^L(t_1)$.] After observing equilibrium output level $q^H(t_1')$ and $q^{L,sep}(t_1')$, entrant's equilibrium beliefs are $\mu(c^H_{inc}|q^H(t_1'), t_1') = 1$ and $\mu(c^H_{inc}|q^{L,sep}(t_1'), t_1') = 0$, respectively.

Note that deviations towards different emission fees $t_1'' \neq t_1'$ do not affect the information transmitted to the entrant through the output levels $q^H(t_1'')$ and $q^{L,sep}(t_1'')$. Indeed, when observing a tax t_1'', the entrant can still check that the incumbent's output level coincides with $q^H(t_1'')$ (inducing him to enter) or with $q^{L,sep}(t_1'')$ (deterring him from entering). Hence, the entrant's beliefs after observing the off-the-equilibrium fee t_1'' are $\mu(c^H_{inc}|q^H(t_1''), t_1'') = 1$ and $\mu(c^H_{inc}|q^{L,sep}(t_1''), t_1'') = 0$.

If, in contrast, the incumbent selects an off-the-equilibrium output function $q(t_1) \neq q^H(t_1) \neq q^{L,sep}(t_1)$, the entrant observes an output level that, for an announced tax t_1, neither coincides with $q^H(t_1)$ nor with $q^{L,sep}(t_1)$. In this case, the entrant cannot infer the incumbent's type after observing the type-independent fee t_1 and the output level $q(t_1)$, and thus her off-the-equilibrium beliefs are $\mu(c^H_{inc}|q(t_1), t_1) = 1$, which holds for any fee t_1.

Operating backwards, let us first analyze the incumbent's output choice for any given first-period tax t_1. The incumbent selects the first-period profit-maximizing output, $q^H(t_1)$, when her marginal costs are high. If the incumbent deviates towards the low-cost incumbent's output $q^{L,sep}(t_1)$, she deters entry. Hence, the high-cost incumbent selects her equilibrium output function $q^H(t_1)$ if $M^H_{inc}(q^H(t_1), t_1) + \delta D^H_{inc} \geq M^H_{inc}(q^{L,sep}(t_1), t_1) + \delta \overline{M}^H_{inc}$ or equivalently,

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

Likewise, if the low-cost incumbent chooses the equilibrium output function $q^{L,sep}(t_1)$, she deters entry. If instead the incumbent deviates towards the high-cost incumbent's output function, $q^H(t_1)$, she attracts entry. Conditional on entry, the low-cost incumbent can select an off-the-equilibrium output $q(t_1) \neq q^H(t_1) \neq q^{L,sep}(t_1)$ that achieves a higher profit than that associated to $q^H(t_1)$. In this case, the incumbent selects an output $q^L(t_1)$, where $q^L(t_1) < q^{L,sep}(t_1)$, which maximizes her profits after entry, yielding $M^L_{inc}(q^L(t_1), t_1) + \delta D^L_{inc}$. Thus, the low-cost incumbent selects her equilibrium output of $q^{L,sep}(t_1)$ if $M^L_{inc}(q^{L,sep}(t_1), t_1) + \delta \overline{M}^L_{inc} \geq M^L_{inc}(q^L(t_1), t_1) + \delta D^L_{inc}$, or equivalently,

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

In addition, the regulator must prefer to set the same per-unit tax to both types of incumbents, i.e., $t_1 = t_1'$. 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 $t_1 = t_1'$ if,

$$SW^{H,E}(t_1', t_2^{H,E}) \geq SW^{H,E}(t_1^H, t_2^{H,E}) \text{ and } SW^{L,NE}(t_1', t_2^{L,NE}) \geq SW^{L,NE}(t_1^L, t_2^{L,NE}) \tag{C3}$$

However, the first inequality in condition C3 cannot hold; given that entry ensues, the regulator would reduce social welfare in the first period by imposing an emission fee $t_1' \neq t_1^H$ without increasing second-period social welfare. 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 $(t_1^H, t_1^{L,sep})$ while the incumbent chooses a type-independent output function $q(t_1)$. After observing equilibrium output levels $q(t_1^H)$ and $q(t_1^{L,sep})$ the entrant's equilibrium beliefs are $\mu(c^H_{inc}|q(t_1^H), t_1^H) = 1$ and $\mu(c^H_{inc}|q(t_1^{L,sep}), t_1^{L,sep}) = 0$, respectively. Likewise, the entrant's off-the-equilibrium beliefs are $\mu(c^H_{inc}|q'(t_1^H), t_1^H) = 1$ and $\mu(c^H_{inc}|q'(t_1^{L,sep}), t_1^{L,sep}) = 0$ after observing emission fee t_1^H and $t_1^{L,sep}$ for any output function $q'(t_1) \neq q^H(t_1) \neq q^{L,sep}(t_1)$. Furthermore, after observing an off-the-equilibrium fee $t_1' \neq t_1^H \neq t_1^{L,sep}$ and output level $q(t_1')$, the entrant's beliefs are $\mu(c^H_{inc}|q(t_1'), t_1') = 1$. And his beliefs are $\mu(c^H_{inc}|q'(t_1'), t_1') = 1$ after observing off-the-equilibrium fee t_1' and off-the-equilibrium output function $q'(t_1) \neq q(t_1)$. For any given emission fee $t_1 \neq t_1^{L,sep}$ entry ensues and the high-cost incumbent selects $q(t_1)$ if $M^H_{inc}(q(t_1), t_1) + \delta D^H_{inc} \geq M^H_{inc}(q^H(t_1), t_1) + \delta D^H_{inc}$, which cannot hold since $q^H(t_1)$ 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 $(t_1^H, t_1^{L,sep})$ where $t_1^{L,sep} \geq t_1^L$ and the incumbent selects output function $q^H(t_1)$ when her costs are high and $q^{L,sep}(t_1)$ when her costs are low.

- *High-cost incumbent.* After observing emission fee t_1^H, the incumbent selects output level $q^H\left(t_1^H\right)$ since $M^H_{inc}(q^H(t_1^H), t_1^H) + \delta D^H_{inc} \geq M^H_{inc}(q^{L,sep}(t_1^H), t_1^H) + \delta D^H_{inc}$ holds given that $q^H(t_1^H)$ maximizes first-period profits. In particular, after observing fee t_1^H but output level

$q^{L,sep}(t_1^H)$, the entrant perceives an inconsistency and, as described in the text, his beliefs are $\mu(c_{inc}^H|q^{L,sep}(t_1^H), t_1^H) = 1$. A similar argument holds for the case in which emission fee t_1^H is followed by deviations to any off-the-equilibrium output function $q(t_1) \neq q^H(t_1) \neq q^{L,sep}(t_1)$, where the entrant's beliefs also induce him to enter. After observing any emission fee $t_1 \neq t_1^H$, the high-cost incumbent chooses $q^H(t_1)$ if

$$M_{inc}^H(q^H(t_1), t_1) + \delta D_{inc}^H \geq M_{inc}^H(q^{L,sep}(t_1), t_1) + \delta \overline{M}_{inc}^H \tag{C1}$$

where entry is deterred when she selects $q^{L,sep}(t_1)$ since $\mu(c_{inc}^H|q^{L,sep}(t_1), t_1) = 0$ for all $t_1 \neq t_1^H$. This holds for the equilibrium fee $t_1 = t_1^{L,sep}$ and for any off-the-equilibrium fee $t_1^{''}$ since, after observing $t_1^{''}$, the entrant only relies on output level $q^{L,sep}(t_1^{''})$ to infer the incumbent's type.

- *Low-cost incumbent.* The incumbent selects output level $q^{L,sep}(t_1^{L,sep})$ after observing the equilibrium emission fee $t_1^{L,sep}$ if

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

is satisfied. A similar argument holds for the case in which emission fee $t_1^{L,sep}$ is followed by deviations to any off-the-equilibrium output function $q(t_1) \neq q^H(t_1) \neq q^{L,sep}(t_1)$. In particular, the type-dependent emission fee allows the entrant to infer the incumbent's type when the output function is $q(t_1)$. Conditional on entry, the most profitable deviation is $q^L(t_1^{L,sep})$. Hence, the low-cost incumbent chooses $q^{L,sep}(t_1^{L,sep})$ if

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

where the entrant infers that the incumbent's cost must be low since output level $q^{L,sep}(t_1^{L,sep})$ confirms the emission fee $t_1^{L,sep}$. A similar argument is applicable for any off-the-equilibrium emission fee $t_1 \neq t_1^H \neq t_1^{L,sep}$,

$$M_{inc}^L(q^{L,sep}(t_1), t_1) + \delta \overline{M}_{inc}^L \geq M_{inc}^L(q^L(t_1), t_1) + \delta D_{inc}^L \tag{C2}$$

since in this case the entrant only relies on the observed output level to infer the incumbent's type. After observing t_1^H, the low-cost incumbent selects $q^{L,sep}(t_1^H)$ if $M_{inc}^L(q^{L,sep}(t_1^H), t_1^H) + \delta D_{inc}^L \geq M_{inc}^L(q^L(t_1^H), t_1^H) + \delta D_{inc}^L$ since, given entry, $q^L(t_1^H)$ maximizes the incumbent's first-period profits. However, this condition cannot hold, and therefore the low-cost incumbent selects $q^{L,sep}(t_1)$ for $t_1 \neq t_1^H$, but $q^L(t_1)$ otherwise.

- *Regulator.* He chooses an emission fee t_1^H when the incumbent's costs are high if $SW^{H,E}(t_1^H, t_2^{H,E}) \geq SW^{H,E}(t_1, t_2^{H,E})$, which holds by definition for any t_1. Specifically, if condition C1 holds, the high-cost incumbent selects $q^H(t_1)$, which attracts entry regardless of the emission fee set by the regulator. If, in contrast, the incumbent's costs are low, from condition C2 the regulator can anticipate that any fee $t_1 \neq t_1^H$ induces the low-cost incumbent to respond with output function $q^{L,sep}(t_1)$, which deters entry. Conditional on no entry, the regulator hence selects the fee level that maximizes $SW^{L,NE}(t_1, t_2^{L,NE})$, provided that the low-cost incumbent responds with $q^{L,sep}(t_1)$, where $q^{L,sep}(t_1) > q^L(t_1)$.

Intuitive Criterion: Conditions C1 and C2 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. In addition, $q^A(t_1) > q^L(t_1)$. We next show that only $q^A(t_1)$ survives the Cho and Kreps' (1987) Intuitive Criterion.

Equilibrium output $q(t_1) \in (q^A(t_1), q^B(t_1)]$. 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 case, the high-cost incumbent obtains $M_{inc}^H(q(t_1), t_1) + \delta \overline{M}_{inc}^H$ which exceeds her 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 $M_{inc}^L(q(t_1), t_1) + \delta \overline{M}_{inc}^L$, which exceeds her equilibrium profits of $M_{inc}^L(q^B(t_1), t_1) + \delta \overline{M}_{inc}^L$ since $M_{inc}^L(q(t_1), t_1) + \delta \overline{M}_{inc}^L$ 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 his posterior beliefs on the incumbent's costs being low, i.e., $\mu(c_{inc}^H | q(t_1), t_1) = 0$, 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 she 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.

Equilibrium output $q(t_1) = q^A(t_1)$**.** 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 she can obtain is $M_{inc}^L(q(t_1), t_1) + \delta \overline{M}_{inc}^L$, which is lower than her equilibrium payoff of $M_{inc}^L(q^A(t_1), t_1) + \delta \overline{M}_{inc}^L$. If instead, she deviates towards $q(t_1) < q^A(t_1)$, she obtains $M_{inc}^L(q(t_1), t_1) + \delta \overline{M}_{inc}^L$, which exceeds her 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 check if the high-cost incumbent also has incentives to deviate towards $q(t_1) \in [q^L(t_1), q^A(t_1))$. The highest profit that she can obtain is $M_{inc}^H(q(t_1), t_1) + \delta \overline{M}_{inc}^H$, which exceeds her equilibrium profit if $M_{inc}^H(q(t_1), t_1) + \delta \overline{M}_{inc}^H > M_{inc}^H(q^H(t_1), t_1) + \delta D_{inc}^H$. This condition can be rewritten as

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

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 his prior beliefs, and chooses to enter if his 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 her 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 $q^A(t_1)$. This is achieved by inducing the socially optimal output $q^L_{SO} = \frac{1 - c^L_{inc}}{1+2d}$ by setting an emission fee t^A_1 that solves $\frac{1 - c^L_{inc}}{1+2d} = q^A(t_1)$.

Regarding the high-cost incumbent, she obtains profits $M^H_{inc}(q(t_1), t_1) + \delta D^H_{inc}$ by deviating towards $q(t_1)$, which are below her 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 $p > \overline{p}$. The regulator can hence induce q^H_{SO} by setting t^H_1 since $q^H(t^H_1) = q^H_{SO}$.

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 her 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 informative equilibrium in which the low-cost incumbent selects $q^A(t_1)$ violates the Intuitive Criterion if $p < \overline{p}$. ■

6.5 *Proof of Proposition 2*

In the uninformative strategy profile, the regulator sets a type-independent emission fee t'_1 and the incumbent selects 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 are $\mu(c^H_{inc}|q(t'_1), t'_1) = p$, which coincide with the prior probability distribution. After observing a deviation from the regulator $t''_1 \neq t'_1$, the entrant's off-the-equilibrium beliefs cannot be updated using Bayes' rule, and for simplicity, we assume that $\mu(c^H_{inc}|q(t''_1), t''_1) = 1$. A similar argument can be made when only the incumbent deviates towards an output function $q'(t'_1) \neq q(t'_1)$ while the regulator still selects t'_1, i.e., $\mu(c^H_{inc}|q'(t'_1), t'_1) = 1$. The same is true when both informed agents deviate, i.e., $\mu(c^H_{inc}|q'(t''_1), t''_1) = 1$.

Therefore, after observing an equilibrium emission fee t'_1 and an equilibrium output level $q(t'_1)$, the entrant enters if his expected profit from entering satisfies $p \times D^H_{ent} + (1-p) \times D^L_{ent} - F > 0$ or $p > \frac{F - D^L_{ent}}{D^H_{ent} - D^L_{ent}} \equiv \overline{p}$, where $\overline{p} \in (0,1)$ by definition. Hence, if $p > \overline{p}$ entry occurs; otherwise the entrant stays out. 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. Let us check the conditions under which the high-cost incumbent chooses output function $q(t_1)$. After observing an equilibrium fee of t'_1, the high-cost incumbent obtains profits $M^H_{inc}(q(t'_1), t'_1) + \delta \overline{M}^H_{inc}$. If, instead, the incumbent deviates towards an off-the-equilibrium output $q'(t'_1) \neq q(t'_1)$, entry ensues and her profits become $M^H_{inc}(q'(t'_1), t'_1) + \delta D^H_{inc}$, which are maximized at $q'(t'_1) = q^H(t'_1)$. Hence, the high-cost incumbent selects $q(t'_1)$ if $M^H_{inc}(q(t'_1), t'_1) + \delta \overline{M}^H_{inc} \geq M^H_{inc}(q^H(t'_1), t'_1) + \delta D^H_{inc}$, or alternatively

$$\delta\left[\overline{M}^H_{inc} - D^H_{inc}\right] \geq M^H_{inc}(q^H(t_1'), t_1') - M^H_{inc}(q(t_1'), t_1') \tag{C4}$$

After observing an off-the-equilibrium fee $t_1'' \neq t_1'$, entry ensues regardless of the incumbent's output function, and therefore $M^H_{inc}(q(t_1''), t_1'') + \delta D^H_{inc} \geq M^H_{inc}(q^H(t_1''), t_1'') + \delta D^H_{inc}$ cannot hold by definition.

Similarly for the low-cost incumbent. If, after observing equilibrium fee t_1', she selects equilibrium output level $q(t_1')$, her profits are $M^L_{inc}(q(t_1'), t_1') + \delta\overline{M}^L_{inc}$. However, if she deviates towards $q'(t_1')$ entry ensues, obtaining profits $M^L_{inc}(q'(t_1'), t_1') + \delta D^L_{inc}$, which are maximized at $q'(t_1') = q^L(t_1')$. Hence, the low-cost incumbent chooses $q(t_1')$ if $M^L_{inc}(q(t_1'), t_1') + \delta\overline{M}^L_{inc} \geq M^L_{inc}(q^L(t_1'), t_1') + \delta D^L_{inc}$, or alternatively

$$\delta\left[\overline{M}^L_{inc} - D^L_{inc}\right] \geq M^L_{inc}(q^L(t_1'), t_1') - M^L_{inc}(q(t_1'), t_1') \tag{C5}$$

After observing an off-the-equilibrium fee $t_1'' \neq t_1'$, entry ensues regardless of the incumbent's output function, and therefore, $q(t_1'')$ is not optimal for the low-cost firm.

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 regulator obtains $SW^{H,NE}(t_1', t_2^{H,NE})$ 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 complete information fee $t_1'' = t_1^H$. Thus, the regulator chooses t_1' if

$$SW^{H,NE}(t_1', t_2^{H,NE}) \geq SW^{H,E}(t_1^H, t_2^{H,E}). \tag{C6a}$$

Therefore, any emission fee t_1' and output function $q(t_1)$ simultaneously satisfying conditions C4-C6 constitutes an uninformative equilibrium of the signaling game.

Intuitive Criterion. We next show that the type-independent output function $q(t_1) = q^L(t_1)$ survives the Cho and Kreps' (1987) Intuitive Criterion, and then demonstrate that, given this output function, only the type-independent fee $t_1' = t_1^L$ survives this equilibrium refinement.

Incumbent, case 1a. Let us first check if the type-independent first-period output function $q(t_1) < q^L(t_1)$ survives the Cho and Kreps' (1987) Intuitive Criterion for any t_1. For simplicity, we first analyze the case where $q(t_1) < q^H(t_1) < q^L(t_1)$ and then that in which $q^H(t_1) < q(t_1) < q^L(t_1)$. On one hand, the highest profit that the low-cost incumbent obtains by deviating towards $q'(t_1) \neq q(t_1)$ is $M^L_{inc}(q'(t_1), t_1) + \delta\overline{M}^L_{inc}$, which exceeds her equilibrium profit $M^L_{inc}(q(t_1), t_1) + \delta\overline{M}^L_{inc}$ for any $q'(t_1) \in (q(t_1), q^L(t_1))$ due to the concavity of $M^L_{inc}(q'(t_1), t_1) + \delta\overline{M}^L_{inc}$. On the other hand, the high-cost incumbent obtains $M^H_{inc}(q(t_1), t_1) + \delta\overline{M}^H_{inc}$ in equilibrium. If instead, she deviates towards $q'(t_1) \neq q(t_1)$, $M^H_{inc}(q'(t_1), t_1) + \delta\overline{M}^H_{inc}$ is the highest profit that she can obtain, which exceeds her equilibrium profit if $q'(t_1) \in (q(t_1), q^H(t_1))$. Hence, beliefs can be restricted to $\mu\left(c^H_{inc} | q'(t_1), t_1\right) = 0$ after observing a deviation $q'(t_1) \in (q^H(t_1), q^L(t_1))$. (Otherwise, the entrant's beliefs are unaffected; since either both types of incumbent, or neither, have incentives to deviate.) Therefore, after observing a deviation $q'(t_1) \in (q^H(t_1), q^L(t_1))$, the entrant believes that the incumbent's cost must be low, and does not enter. Under these updated beliefs, the profit obtained by the low-cost incumbent from deviating exceeds her equilibrium profits. Hence, the low-cost incumbent deviates towards $q'(t_1)$ and the uninformative PBE where $q(t_1) < q^H(t_1) < q^L(t_1)$ violates the Intuitive Criterion for any emission fee t_1.

Let us now examine the case where the equilibrium output function $q(t_1)$ satisfies $q^H(t_1) < q(t_1) < q^L(t_1)$. On one hand, the highest profit that the low-cost incumbent can obtain by deviating towards $q'(t_1) \neq q(t_1)$ is $M^L_{inc}(q'(t_1), t_1) + \delta \overline{M}^L_{inc}$, which exceeds her equilibrium profit of $M^L_{inc}(q(t_1), t_1) + \delta \overline{M}^L_{inc}$ for any $q'(t_1) \in (q(t_1), q^L(t_1)]$. On the other hand, the highest profit that the high-cost incumbent can obtain by deviating towards $q'(t_1) \neq q(t_1)$ is $M^H_{inc}(q'(t_1), t_1) + \delta \overline{M}^H_{inc}$, which exceeds her equilibrium profit of $M^H_{inc}(q(t_1), t_1) + \delta \overline{M}^H_{inc}$ for any $q'(t_1) \in [q^H(t_1), q(t_1))$. Therefore, after observing any deviation $q'(t_1) \in (q(t_1), q^L(t_1)]$, the entrant believes that the incumbent's costs must be low, and does not enter. Under these updated beliefs, the profit that the low-cost incumbent obtains deviating exceeds her equilibrium profits. Hence, the uninformative PBE where $q(t_1) < q^L(t_1)$ also violates the Intuitive Criterion.

Incumbent, case 1b. Next let us check if the type-independent first-period output $q(t_1) > q^L(t_1)$ survives the Cho and Kreps' (1987) Intuitive Criterion. On one hand, the low-cost incumbent obtains $M^L_{inc}(q(t_1), t_1) + \delta \overline{M}^L_{inc}$ in equilibrium. By instead deviating towards $q^L(t_1)$, $M^L_{inc}(q^L(t_1), t_1) + \delta \overline{M}^L_{inc}$ is the highest profit she can obtain, which exceeds her equilibrium profits. On the other hand, the high-cost incumbent obtains $M^H_{inc}(q(t_1), t_1) + \delta \overline{M}^H_{inc}$ in equilibrium. By deviating towards $q^L(t_1)$, $M^H_{inc}(q^L(t_1), t_1) + \delta \overline{M}^H_{inc}$ is the highest profit she obtains after no entry, which also exceeds her equilibrium profits, given that $q^H(t_1) < q^L(t_1) < q(t_1)$. Therefore, both types of incumbent have incentives to deviate towards $q^L(t_1)$ and entrant's beliefs cannot be updated, i.e., $\mu\left(c^H_{inc}|q^L(t_1), t_1\right) = p$ inducing no entry. Given these beliefs, both types of incumbent deviate toward $q^L(t_1)$, obtaining higher profits than in equilibrium. Hence, the uninformative PBE in which both types select $q(t_1) > q^L(t_1)$ also violates the Intuitive Criterion.

Incumbent, case 1c. Let us now check if the type-independent first-period output $q(t_1) = q^L(t_1)$ survives the Cho and Kreps' (1987) Intuitive Criterion. On one hand, $M^L_{inc}(q'(t_1), t_1) + \delta \overline{M}^L_{inc}$ is the highest payoff the low-cost incumbent obtains by deviating towards $q'(t_1) \neq q^L(t_1)$, which lies below her equilibrium profits since $M^L_{inc}(q'(t_1), t_1) + \delta \overline{M}^L_{inc}$ reaches its maximum at exactly $q'(t_1) = q^L(t_1)$. Hence, the low-cost incumbent does not have incentives to deviate from the type-independent output function $q(t_1) = q^L(t_1)$. On the other hand, $M^H_{inc}(q'(t_1), t_1) + \delta \overline{M}^H_{inc}$ is the highest payoff the high-cost incumbent can obtain by deviating toward $q'(t_1) \neq q^L(t_1)$. Therefore, the high-cost incumbent does not have incentives to deviate if $M^H_{inc}(q^L(t_1), t_1) + \delta \overline{M}^H_{inc} \geq M^H_{inc}(q'(t_1), t_1) + \delta \overline{M}^H_{inc}$, which only holds for deviations closer to her first-period profit-maximizing output, i.e., $q'(t_1) \in [q^H(t_1), q^L(t_1))$. Hence, the entrant believes with certainty the incumbent is a high type for every deviation in this interval, i.e., $\mu\left(c^H_{inc}|q'(t_1), t_1\right) = 1$, and enters. In contrast, his updated beliefs are unaffected after observing any other deviation. The high-cost incumbent's profits from deviating towards $q'(t_1)$ are hence $M^H_{inc}(q'(t_1), t_1) + \delta D^H_{inc}$, which are lower than her equilibrium profits if

$$M_{inc}^{H}(q^{L}(t_1), t_1) + \delta \overline{M}_{inc}^{H} \geq M_{inc}^{H}(q'(t_1), t_1) + \delta D_{inc}^{H} \tag{C7}$$

Note that deviation profits, $M_{inc}^{H}(q'(t_1), t_1) + \delta D_{inc}^{H}$, are maximal at $q'(t_1) = q^{H}(t_1)$, yielding profits of $M_{inc}^{H}(q^{H}(t_1), t_1) + \delta D_{inc}^{H}$. Hence, if $M_{inc}^{H}(q^{L}(t_1), t_1) + \delta \overline{M}_{inc}^{H} \geq M_{inc}^{H}(q^{H}(t_1), t_1) + \delta D_{inc}^{H}$, then condition C7 holds for all deviations $q'(t_1) \in [q^{H}(t_1), q^{L}(t_1))$. Note that the last inequality holds since the equilibrium output function $q(t_1) = q^{L}(t_1)$ satisfies condition C4. Therefore, the high-cost incumbent does not have incentives to deviate from $q^{L}(t_1)$, and the type-independent output function $q^{L}(t_1)$ must be part of an uninformative equilibrium surviving the Intuitive Criterion.

Regulator, case 2a. Given output function $q^{L}(t_1)$ selected by both types of incumbent, let us finally analyze the regulator's equilibrium emission fee t_1'. Let us first consider the case where $t_1' < t_1^{L}$. For simplicity, we first analyze the case where $t_1^{H} < t_1' < t_1^{L}$ and then $t_1' < t_1^{H} < t_1^{L}$. The regulator facing a low-cost incumbent obtains an equilibrium social welfare of $SW^{L,NE}(t_1', t_2^{L,NE})$. By deviating towards an off-the-equilibrium fee of $t_1^{L} \neq t_1'$, $SW^{L,NE}(t_1^{L}, t_2^{L,NE})$ is the highest payoff that the regulator obtains. (As described in the paper, $SW^{H,NE}(t_1^{L}, t_2^{H,NE}) > SW^{H,E}(t_1^{L}, t_2^{H,E})$ since the first-period social cost from over-taxation coincides in both cases, given that the regulator sets the same fee t_1^{L}, whereas second-period social welfare is larger under no entry.) This deviating payoff exceeds his equilibrium welfare given that $SW^{L,NE}(t_1^{L}, t_2^{L,NE}) \geq SW^{L,NE}(t_1', t_2^{L,NE})$, since t_1^{L} maximizes social welfare conditional on no entry. On the other hand, the regulator facing a high-cost incumbent obtains an equilibrium social welfare of $SW^{H,NE}(t_1', t_2^{H,NE})$. By deviating towards an off-the-equilibrium fee of $t_1^{L} \neq t_1'$, $SW^{H,NE}(t_1^{L}, t_2^{H,NE})$ is the highest payoff that the regulator obtains when entry is deterred, which does not exceed his equilibrium welfare since $SW^{H,NE}(t_1^{L}, t_2^{H,NE}) < SW^{H,NE}(t_1', t_2^{H,NE})$, given that $t_1^{H} < t_1' < t_1^{L}$. Therefore, after observing a deviation $t_1^{L} \neq t_1'$, the entrant believes that the incumbent's cost must be low, and does not enter. Under these updated beliefs, the social welfare from deviating to t_1^{L}, $SW^{L,NE}(t_1^{L}, t_2^{L,NE})$, exceeds that in equilibrium, $SW^{L,NE}(t_1', t_2^{L,NE})$. Hence, the regulator facing a low-cost incumbent deviates towards t_1^{L} and the uninformative PBE where the regulator selects the type-independent fee t_1' where $t_1^{H} < t_1' < t_1^{L}$ violates the Intuitive Criterion.

Second, let us now consider the case where $t_1' < t_1^{H} < t_1^{L}$. On one hand, the regulator facing a low-cost incumbent obtains an equilibrium social welfare of $SW^{L,NE}(t_1', t_2^{L,NE})$. By deviating towards an off-the-equilibrium fee of $t_1'' \neq t_1'$, $SW^{L,NE}(t_1'', t_2^{L,NE})$ is the highest payoff that the regulator obtains, which exceeds equilibrium welfare if $SW^{L,NE}(t_1'', t_2^{L,NE}) \geq SW^{L,NE}(t_1', t_2^{L,NE})$, which is satisfied for all $t_1'' \in (t_1', t_1^{L}]$ since t_1^{L} maximizes social welfare conditional on no entry. On the other hand, the regulator facing a high-cost incumbent obtains an equilibrium social welfare of $SW^{H,NE}(t_1', t_2^{H,NE})$. By deviating towards an off-the-equilibrium fee of $t_1'' \neq t_1'$, $SW^{H,NE}(t_1'', t_2^{H,NE})$ is the highest payoff that the regulator obtains, which exceeds equilibrium welfare for all $t_1'' \in (t_1', t_1^{H}]$. Therefore, after observing a deviation $t_1'' \in (t_1^{H}, t_1^{L}]$, the entrant believes that the incumbent's cost must be low, and does not enter. Under these updated beliefs, the social welfare from deviating to $t_1'' \in (t_1^H, t_1^L]$, exceeds that in equilibrium, $SW^{L,NE}(t_1', t_2^{L,NE})$. Hence, the regulator facing a low-cost incumbent deviates towards t_1'' and the uninformative PBE where the regulator selects a type-independent fee t_1', where $t_1' < t_1^H < t_1^L$, also violates the Intuitive Criterion.

Regulator, case 2b. Let us now examine the case where the equilibrium emission fee t_1' satisfies $t_1' > t_1^L$. On one hand, the regulator facing a low-cost incumbent obtains an equilibrium social welfare of $SW^{L,NE}(t_1', t_2^{L,NE})$. By deviating towards an off-the-equilibrium fee of $t_1^L \neq t_1'$ the highest payoff that the regulator can obtain occurs when entry is deterred, yielding welfare of $SW^{L,NE}(t_1^L, t_2^{L,NE})$, which exceeds his equilibrium welfare since $SW^{L,NE}(t_1^L, t_2^{L,NE}) \geq SW^{L,NE}(t_1', t_2^{L,NE})$. On the other hand, the regulator facing a high-cost incumbent obtains an equilibrium social welfare of $SW^{H,NE}(t_1', t_2^{H,NE})$. By deviating towards an off-the-equilibrium fee of $t_1^L \neq t_1'$, $SW^{H,NE}(t_1^L, t_2^{H,NE})$ is the highest payoff that the regulator obtains, which exceeds his equilibrium welfare since $SW^{H,NE}(t_1^L, t_2^{H,NE}) \geq SW^{H,NE}(t_1', t_2^{H,NE})$, given that $t_1^H < t_1^L < t_1'$. Therefore, the regulator has incentives to deviate towards t_1^L for both types of incumbent and the entrant's beliefs cannot be updated, i.e., $\mu\left(c_{inc}^H | q^L(t_1^L), t_1^L\right) = p$ inducing no entry since $p < \overline{p}$. Given these beliefs, the regulator has incentives to deviate toward t_1^L, obtaining higher social welfare than in equilibrium. Hence, the uninformative strategy profile where the regulator selects $t_1' > t_1^L$ also violates the Intuitive Criterion.

Regulator, case 2c. Let us finally analyze the case where the equilibrium emission fee t_1' satisfies $t_1' = t_1^L$. On one hand, the regulator facing a low-cost incumbent obtains an equilibrium social welfare of $SW^{L,NE}(t_1^L, t_2^{L,NE})$. By deviating towards an off-the-equilibrium fee of $t_1'' \neq t_1^L$ the highest payoff that the regulator can obtain occurs when entry is deterred, yielding welfare of $SW^{L,NE}(t_1'', t_2^{L,NE})$, which is strictly lower than the equilibrium welfare of $SW^{L,NE}(t_1^L, t_2^{L,NE})$. On the other hand, the regulator facing a high-cost incumbent obtains an equilibrium social welfare of $SW^{H,NE}(t_1^L, t_2^{H,NE})$. By deviating towards an off-the-equilibrium fee of $t_1'' \neq t_1^L$, $SW^{H,NE}(t_1'', t_2^{H,NE})$ is the highest payoff that the regulator obtains, which exceeds the equilibrium welfare if

$$SW^{H,NE}(t_1'', t_2^{H,NE}) \geq SW^{H,NE}(t_1^L, t_2^{H,NE}),$$

which holds for any deviation $t_1'' \in [t_1^H, t_1^L)$. Hence, the entrant assigns full probability to the cost being high for every deviation $t_1'' \in [t_1^H, t_1^L)$, i.e., $\mu\left(c_{inc}^H | q^L(t_1''), t_1''\right) = 1$, and entry ensues. Given these updated beliefs, the social welfare that the regulator facing a high-cost incumbent obtains when he deviates towards an emission fee of t_1'' is $SW^{H,E}(t_1'', t_2^{H,E})$, which is lower than his equilibrium welfare if $SW^{H,E}(t_1'', t_2^{H,E}) < SW^{H,NE}(t_1^L, t_2^{H,NE})$. This condition holds since, according to condition C6a, the equilibrium fee t_1^L must satisfy $SW^{H,E}(t_1^H, t_2^{H,E}) < SW^{H,NE}(t_1^L, t_2^{H,NE})$. We can hence conclude that

$$SW^{H,E}(t_1'', t_2^{H,E}) < SW^{H,E}(t_1^H, t_2^{H,E}) < SW^{H,NE}(t_1^L, t_2^{H,NE})$$

since t_1^H maximizes $SW^{H,E}(t_1, t_2^{H,E})$. Therefore, the regulator facing a high-cost incumbent does not have incentives to deviate either, and the uninformative PBE where the regulator selects t_1^L

survives the Intuitive Criterion.

Hence, the regulator selects t_1^L when $SW^{H,NE}(t_1^L, t_2^{H,NE}) > SW^{H,E}(t_1^H, t_2^{H,E})$, where expression $SW^{H,NE}(t_1^L, t_2^{H,NE})$ embodies both first- and second-period welfare, $W_1^H(t_1^L)$ and $W_2^{H,NE}(t_2^{H,NE})$, respectively; and $SW^{H,E}(t_1^H, t_2^{H,E})$ is composed by $W_1^H(t_1^H)$ and $\left[W_2^{H,E}(t_2^{H,E}) - F\right]$. Thus, the regulator chooses t_1^L if

$$W_1^H(t_1^L) + \delta W_2^{H,NE}(t_2^{H,NE}) > W_1^H(t_1^H) + \delta \left[W_2^{H,E}(t_2^{H,E}) - F\right].$$

Given that second-period fees $t_2^{H,NE}$ and $t_2^{H,E}$ induce the same output level, then $W_2^{H,NE}(t_2^{H,NE}) = W_2^{H,E}(t_2^{H,E})$. As a consequence, the above inequality reduces to $F > \frac{W_1^H(t_1^H) - W_1^H(t_1^L)}{\delta}$, where $W_1^H(t_1^H) - W_1^H(t_1^L)$ measures the first-period welfare loss from overtaxation. ■

6.6 *Proof of Corollary 1*

Let us focus on first-period welfare, since second-period production levels and emission fees coincide in the informative equilibrium and the complete information settings. The first-period production under complete information is $q^L(t_1^L) = q_{SO}^L$, which coincides with the production level in the informative equilibrium, $q^A(t_1^A) = q_{SO}^L$. Hence, first-period consumer surplus are equal in both information contexts. A similar argument applies to the environmental damage from pollution. The sum of producer surplus and tax collection in both settings also coincide, since under complete information producer surplus is $(1 - q_{SO}^L)q_{SO}^L - \left(c_{inc}^L + t_1^A\right) q_{SO}^L + t_1^A q_{SO}^L$, and under the informative equilibrium it is $(1 - q_{SO}^L)q_{SO}^L - \left(c_{inc}^L + t_1^L\right) q_{SO}^L + t_1^L q_{SO}^L$. Finally, note that the overall social welfare when the incumbent's costs are high coincides in both information settings since the same output level q_{SO}^H are induced by the same emission fees.

Social welfare in the uninformative equilibrium, $SW^{H,NE}(t_1^L, t_2^{H,NE})$, is unambiguously larger than that under complete information $SW^{H,E}(t_1^H, t_2^{H,E})$ since, $SW^{H,NE}(t_1^L, t_2^{H,NE}) \geq SW^{H,E}(t_1^H, t_2^{H,E})$ holds by definition from Proposition 2. ■

6.7 *Proof of Proposition 3*

Similarly to the proof of Proposition 1, we first show that strategy profiles where only one (both) informed agents select a type-dependent action cannot (can, respectively) be sustained as a 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 that 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 entering). 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 $M_{inc}^H(q^H(t), t) + \delta D_{inc}^H(t) \geq M_{inc}^H(q^{L,sep}(t), t) + \delta \overline{M}_{inc}^H(t)$ or equivalently,

$$M_{inc}^H(q^H(t), t) - M_{inc}^H(q^{L,sep}(t), t) \geq \delta \left[\overline{M}_{inc}^H(t) - D_{inc}^H(t)\right] \tag{C8}$$

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 after entry, yielding $M_{inc}^L(q^L(t), t) + \delta D_{inc}^L(t)$. Thus, the low-cost incumbent selects her equilibrium output of $q^{L,sep}(t)$ if $M_{inc}^L(q^{L,sep}(t), t) + \delta \overline{M}_{inc}^L(t) \geq M_{inc}^L(q^L(t), t) + \delta D_{inc}^L(t)$, or equivalently,

$$M_{inc}^L(q^L(t), t) - M_{inc}^L(q^{L,sep}(t), t) \leq \delta \left[\overline{M}_{inc}^L(t) - D_{inc}^L(t)\right] \tag{C9}$$

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,

$$SW^{H,E}(t') \geq SW^{H,E}(t^{H,E}) \text{ and } SW^{L,NE}(t') \geq SW^{L,NE}(t^{L,NE}) \tag{C10}$$

However, the first inequality in condition C10 cannot hold; given that entry ensues, the regulator would reduce social welfare by imposing an emission fee $t' \neq t^{H,E}$. 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 $\mu(c_{inc}^H|q(t^{H,E}), t^{H,E}) = 1$ and $\mu(c_{inc}^H|q(t^{L,sep}), t^{L,sep}) = 0$, respectively. Likewise, the entrant's off-the-equilibrium beliefs are $\mu(c_{inc}^{H}|q'(t^{H,E}),t^{H,E})=1$ and $\mu(c_{inc}^{H}|q'(t^{L,sep}),t^{L,sep})=0$ 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 $\mu(c_{inc}^{H}|q(t'),t')=1$. And his beliefs are $\mu(c_{inc}^{H}|q'(t'),t')=1$ 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 $M_{inc}^{H}(q(t),t)+\delta D_{inc}^{H}(t)\geq M_{inc}^{H}(q^{H}(t),t)+\delta D_{inc}^{H}(t)$, 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 $M_{inc}^{H}(q^{H}(t^{H,E}),t^{H,E})+\delta D_{inc}^{H}(t^{H,E})\geq M_{inc}^{H}(q^{L,sep}(t^{H,E}),t^{H,E})+\delta D_{inc}^{H}(t^{H,E})$ 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 $\mu(c_{inc}^{H}|q^{L,sep}(t^{H,E}),t^{H,E})=1$. 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

$$M_{inc}^{H}(q^{H}(t),t)+\delta D_{inc}^{H}(t)\geq M_{inc}^{H}(q^{L,sep}(t),t)+\delta\overline{M}_{inc}^{H}(t) \tag{C8}$$

  where entry is deterred when she selects $q^{L,sep}(t)$ since $\mu(c_{inc}^{H}|q^{L,sep}(t),t)=0$ 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

$$M_{inc}^{L}(q^{L,sep}(t^{L,sep}),t^{L,sep})+\delta\overline{M}_{inc}^{L}(t^{L,sep})\geq M_{inc}^{L}(q^{H}(t^{L,sep}),t^{L,sep})+\delta D_{inc}^{L}(t^{L,sep})$$

  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

$$M_{inc}^{L}(q^{L,sep}(t^{L,sep}),t^{L,sep})+\delta\overline{M}_{inc}^{L}(t^{L,sep})\geq M_{inc}^{L}(q^{L}(t^{L,sep}),t^{L,sep})+\delta D_{inc}^{L}(t^{L,sep})$$

  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 $t \neq t^{H,E} \neq t^{L,sep}$,

$$M^L_{inc}(q^{L,sep}(t), t) + \delta \overline{M}^L_{inc}(t) \geq M^L_{inc}(q^L(t), t) + \delta D^L_{inc}(t) \tag{C9}$$

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 $\widetilde{t}^A$ since, provided that condition C9 holds, the entrant stays out after observing output level $q^{L,sep}(t)$ for any fee $t \neq \widetilde{t}^A$. 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 $\tilde{q}^A(t)$ in the first period and output function $x^{L,NE}_{inc}(t)$ in the second period). That is, the regulator solves

$$\min_t \ |DWL_1(t)| + \delta_R \, |DWL_2(t)|$$

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

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

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

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

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

By a similar argument as in the proof of Proposition 1, it is easy to show that only the informative equilibrium where the regulator sets a tax pair $\left(t^{H,E}, \widetilde{t}^A\right)$, the high-cost incumbent selects an output function $q^H(t)$, and the low-cost incumbent chooses output function $q^{L,Sep}(t) = \widetilde{q}^A(t)$, where $\widetilde{q}^A(t)$ solves condition C8 with equality, survives the Cho and Kreps' Intuitive Criterion.

Finally, note that probability cutoff $\overline{p}(t^{L,NE})$ under an inflexible policy is lower than that under a flexible policy, $\overline{p}$. Specifically, $\overline{p}(t^{L,NE}) < \overline{p}$ implies

$$\frac{F - D^{L}_{ent}\left(t^{L,NE}\right)}{D^{H}_{ent}\left(t^{L,NE}\right) - D^{L}_{ent}\left(t^{L,NE}\right)} < \frac{F - D^{L}_{ent}\left(t^{L,E}_{2}\right)}{D^{H}_{ent}\left(t^{H,E}_{2}\right) - D^{L}_{ent}\left(t^{L,E}_{2}\right)}$$

rearranging, we obtain $\frac{D^{L}_{ent}\left(t^{L,NE}\right)}{D^{H}_{ent}\left(t^{L,NE}\right)} > \frac{D^{L}_{ent}\left(t^{L,E}_{2}\right)}{D^{H}_{ent}\left(t^{H,E}_{2}\right)}$. This inequality holds since the left-hand side only measures the loss in profits that the entrant experiences from dealing with a low-cost incumbent given a constant fee $t^{L,NE}$, whereas the right-hand side measures, in addition, the reduction in the entrant's profits due to the more stringent fee $t^{L,E}_{2} > t^{H,E}_{2} > t^{L,NE}$. ■

6.8 *Proof of Proposition 4*

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 $\mu(c^{H}_{inc}|q(t'), t') = p$, 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 $\mu(c^{H}_{inc}|q(t''), t'') = 1$. 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., $\mu(c^{H}_{inc}|q'(t'), t') = 1$. The same is true when both informed agents deviate, i.e., $\mu(c^{H}_{inc}|q'(t''), t'') = 1$.

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 $p \times D^{H}_{ent}(t') + (1-p) \times D^{L}_{ent}(t') - F > 0$ or $p > \frac{F - D^{L}_{ent}(t')}{D^{H}_{ent}(t') - D^{L}_{ent}(t')} \equiv \overline{p}(t')$. 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. 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 $M^{H}_{inc}(q(t'), t') + \delta \overline{M}^{H}_{inc}(t')$. If, instead, the incumbent deviates towards an off-the-equilibrium output $q'(t') \neq q(t')$, entry ensues and her profits become $M^{H}_{inc}(q'(t'), t') + \delta D^{H}_{inc}(t')$, which are maximized at $q'(t') = q^{H}(t')$. Hence, the high-cost incumbent selects $q(t')$ if $M^{H}_{inc}(q(t'), t') + \delta \overline{M}^{H}_{inc}(t') \geq M^{H}_{inc}(q^{H}(t'), t') + \delta D^{H}_{inc}(t')$, or alternatively

$$\delta \left[\overline{M}^{H}_{inc}(t') - D^{H}_{inc}(t')\right] \geq M^{H}_{inc}(q^{H}(t'), t') - M^{H}_{inc}(q(t'), t') \tag{C11}$$

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

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

$$\delta \left[\overline{M}^L_{inc}(t') - D^L_{inc}(t')\right] \geq M^L_{inc}(q^L(t'), t') - M^L_{inc}(q(t'), t') \tag{C12}$$

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.

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

$$SW^{H,NE}(t') \geq SW^{H,E}(t^{H,E}). \tag{C13a}$$

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

$$SW^{L,NE}(t') \geq SW^{L,E}(t^{L,E}). \tag{C13b}$$

Therefore, any emission fee t' and output function $q(t)$ simultaneously satisfying conditions C11-C13 constitutes an uninformative equilibrium of the signaling game. Using a similar argument as in the proof of Proposition 2, 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 $p \leq \overline{p}(t^{L,NE})$ ■

6.9 *Proof of Corollary 2*

Informative equilibrium vs. Complete information. The informative equilibrium induces an output level of $\widetilde{q}^A(\widetilde{t}^A)$, which exceeds that under complete information, $q^L(t^{L,NE})$, where $q^L(t^{L,NE}) = q^L(t^L_1) = q^L_{SO}$ given that $t^{L,NE} = t^L_1$. Then, the first-period overproduction in the informative equilibrium of Proposition 3, i.e., $\widetilde{q}^A(\widetilde{t}^A) > q^L_{SO}$, entails a welfare loss. Similarly, in the second period, the incumbent maintains its monopoly power, producing according to output function $x^{L,NE}_{inc}(t)$, 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 $x^{L,NE}_{inc}(t^{L,NE}) = q^L(t^{L,NE}) = q^L_{SO}$. In contrast, in the informative equilibrium the more stringent fee $\widetilde{t}^A$ induces a lower output level, i.e., $x^{L,NE}_{inc}(\widetilde{t}^A) < q^L_{SO}$ since $\widetilde{t}^A > t^{L,NE}$. 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.

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 $q^H(t_1^H) = q_{SO}^H$ given that $t_1^H < t^{H,E}$. 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 $t^{H,E} < t_2^{H,E}$. 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. We next evaluate social welfare in each case to determine which information setting yields the largest social welfare. In the uninformative equilibrium, emission fee $t^{L,NE}$ and output function $q^L(t)$ yield a first-period social welfare of

$$\frac{(1 - c_{inc}^L)\left[1 - 2c_{inc}^H + c_{inc}^L\right]}{2A} \tag{A.4}$$

while in the second-period game, the (same) fee $t^{L,NE}$ and output function $x_{inc}^{H,NE}(t)$, given that entry is deterred in the uninformative equilibrium, entail a welfare of

$$\frac{\left[\left(R^2 - 4\right)\left(c_{inc}^H\right)^2 + R^2\left(c_{inc}^L\right)^2 + c_{inc}^H\left(8 - 2R^2 c_{inc}^L\right) - 4\right]}{8A} \tag{A.5}$$

where $R \equiv 1 - 2d$. In the complete information setting, the equilibrium fee $t^{H,E}$ and output function $q^H(t)$ produce a first-period social welfare of

$$\frac{3(3 + 4\delta)(9 + 20\delta)(1 - c_{inc}^H)^2}{2A \times G^2} \tag{A.6}$$

where $G \equiv 9 + 16\delta$; whereas in the second-period game, $t^{H,E}$ and output function $x_{inc}^{H,E}(t)$ from the incumbent and $x_{ent}^{H,E}(t)$ from the entrant, given that entry ensues under complete information, entail a welfare of

$$\frac{4(3 + 4\delta)(3 + 8\delta)(1 - c_{inc}^H)^2}{A \times G^2} - F \tag{A.7}$$

Comparing the above expressions, we obtain that overall social welfare under the uninformative equilibrium (discounted sum of expression A.4-A.5) exceeds that under complete information (discounted sum of expression A.6-A.7) if parameter d is sufficiently high, i.e., $d > d_{Inflex}$, where

$$d_{Inflex} \equiv \frac{1}{2} + \frac{10F - \sqrt{100F^2 - (c_{inc}^H - c_{inc}^L)^2 L}}{5(c_{inc}^H - c_{inc}^L)^2}$$

where $L \equiv 25(c^L_{inc})^2 + c^H_{inc}(2 - 50c^L_{inc}) + 24\left(c^H_{inc}\right)^2 - 100F - 1.$ ■

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