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Environmental Protection Agencies: Measuring the Welfare Benefits from Regulation under Different Information Contexts

By

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Measuring the Welfare Benefits from Regulation under Different Information Contexts

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Abstract

This paper evaluates the welfare benefits of introducing environmental regulation in a market that is subject to the threat of entry. We consider complete and incomplete information settings, where potential entrants use the regulator's tax policy and the incumbent's output decisions in order to infer the incumbent's cost structure. When the regulator is absent, we show that firms' entry-deterring practices increase pollution relative to complete information. Hence, under certain conditions, environmental regulation becomes more beneficial in incomplete than in complete information contexts. Our results, therefore, identify under which cases an under- or over-estimation of the welfare benefits of environmental regulation arises from ignoring the information setting in which firms interact. We also examine how this estimation error increases as firms become more symmetric in their production costs.

KEYWORDS: Entry deterrence; Signaling; Emission fees; Welfare Benefits.
JEL CLASSIFICATION: D82, H23, L12, Q5

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1 Introduction

The role of the United States' Environmental Protection Agency (EPA) has recently been under the scrutiny of both politicians and lobbyists. Coinciding with its 40th anniversary, several politicians became especially vocal in their criticisms of the agency on the basis that its regulations hinder firms' competitiveness by reducing their ability to adjust their production facilities, thereby negatively affecting firms' capacity to create jobs and promote economic growth.[1]

Our paper contributes to this debate by evaluating the welfare benefits from environmental regulation, measured as the difference between social welfare when the regulator is present and absent, and then comparing these welfare benefits in different information contexts. Specifically, we show that ignoring the information setting in which the industry operates can lead to a systematic under- or over-estimation of the welfare-improving effects of regulation. This result implies that, under certain conditions, the task of the regulatory agency yields large welfare benefits when firms interact in incomplete information frameworks, making environmental policy especially necessary in these settings.

We consider an entry-deterrence model where a monopolist has operated for a long period of time. Because production generates a negative externality, this incumbent has been subject to environmental regulation for an extended period, allowing the regulator to accumulate relatively accurate information about the incumbent's costs. This setting describes, for instance, power generating companies that use fossil fuels as their primary input, since they are regarded as regional monopolies in several states across the U.S.[2] and, in addition, have faced environmental regulations from the EPA since the agency's inception in 1970.[3] Unlike the regulator, potential entrants have access to less precise information about the incumbent's costs. As a consequence, the entrant bases its entry decision upon the information it infers after observing two signals: the emission fee that the regulator imposes on the incumbent *and* the firm's output decision.

We investigate the welfare benefits of environmental regulation under two information settings: complete and incomplete information. As a benchmark for comparison, we first analyze a complete information context, where all agents are perfectly informed about the incumbent's cost structure. Our results show that an inefficiency arises when the regulator is absent, given that firms do not internalize the negative effects of their pollution on social welfare. The presence of the regula-

[1] Some House Republicans have been especially critical in their statements. For instance, the Chairman of the House Interior and Environment Appropriations Subcommittee, mentioned on July 12, 2011, that "the scariest agency in the federal government is the EPA... an agency that has lost its bearings." Similarly, the Chairman of the Transportation and Infrastructure Committee, expressed his concerns that the "EPA's 'regulatory jihad' is strangling any chance of economic recovery." Several Democrats have also criticized the EPA. For example, in March 2011, representatives from Minnesota, West Virginia, and Oklahoma joined a bill supported by 43 Senate Republicans that would bar the EPA from using federal law to control greenhouse gases from refineries and other industrial facilities; Capiello (2011). Finally, Mufson (2008) reports that lobbyists such as AmericasPower.org have launched a $30 million advertising campaign against the EPA's regulation of CO2 emissions.

[2] According to Slocum (2007), for instance, 92% of U.S. households have no ability to choose an alternative electricity supplier, since the wholesale market of power generation is essentially monopolized.

[3] Coal-fired power plants, for instance, are generally considered regional monopolies that have continually faced environmental regulations. 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.

tor hence becomes welfare improving, since environmental regulation induces the socially optimal output; a result that is consistent with the existing literature.

We then examine an incomplete information setting, where the potential entrant does not observe the incumbent's costs, but assigns a prior probability to these costs being either high or low. When the probability of facing a high-cost incumbent is sufficiently large, an "informative" equilibrium can be supported, in which information about the incumbent's costs is conveyed to the entrant. Without regulation, this equilibrium prescribes that the low-cost incumbent overproduces, relative to complete information, in order to reveal its efficient cost structure to the potential entrant, thus deterring entry. Such overproduction, however, generates more pollution, suggesting that an additional form of inefficiency emerges, stemming from the incomplete information setting in which firms operate. As a result, the introduction of environmental regulation entails larger welfare benefits under incomplete than under complete information. We furthermore show that the welfare benefits of regulation increase when the cost differential between incumbent and entrant is small. In this case, the low-cost incumbent faces the threat of a "tough" competitor and, hence, is willing to substantially overproduce in order to signal its type to the potential entrant, thus deterring entry. Such overproduction, however, entails an increase in pollution, thereby making the regulatory agency's task more beneficial.

Our findings suggest implications for the assessment of the welfare benefits of environmental regulation. Specifically, if firms are relatively symmetric in their cost structure, a regulator who assumes that the industry operates under complete information —while, in fact, potential entrants do not observe the incumbent's costs— would underestimate the welfare benefits of regulation. By contrast, when firms are asymmetric in their costs, our results imply that the regulator can essentially ignore the information context in which the industry operates, given that the welfare benefits from intervention are similar in both information settings.

In the context of low priors, we demonstrate that, when the regulatory agency is absent, an "uninformative" equilibrium can be sustained where the high-cost incumbent mimics the output decision of the low-cost firm, i.e., the high-cost incumbent overproduces relative to complete information. Such a mimicking strategy conceals information from the potential entrant, who is deterred from the industry. Importantly, the introduction of incomplete information, therefore, gives rise to both positive and negative welfare effects. On one hand, the incumbent's first-period overproduction increases pollution but, on the other hand, deterrence of the potential entrant reduces second-period pollution relative to the complete information game, where entry ensues and aggregate pollution increases. When first-period overproduction is large —which occurs when the cost differential between high- and low-type incumbent is strong— the negative effect dominates, and social welfare under incomplete information is smaller than under the complete information setting. Otherwise, social welfare under incomplete information environments is larger. These findings suggest policy implications for contexts where the EPA is absent, e.g., it does not set emission fees. In particular, the regulatory agency can still improve social welfare by strategically revealing information about the incumbent's cost structure to potential entrants when the cost differential among firms is large, or by concealing such information otherwise.

When the regulator is present, our paper shows that the uninformative equilibrium can only be supported under more restrictive conditions. Therefore, the presence of environmental regulation hinders the incumbent's ability to conceal its type and deter entry, thus entailing a welfare benefit relative to settings where the regulator is absent. Furthermore, such welfare benefit becomes larger as the overproduction of the unregulated high-cost incumbent increases, i.e., when firms are cost-asymmetric.

Summarizing, when firms are relatively symmetric in their cost structure and priors are low, a regulator who ignores the incomplete information setting where the industry operates would overestimate the welfare benefits of regulation, a result that differs from that when priors are high. Intuitively, when the regulator is absent and priors are high, an informative equilibrium emerges in which overproduction (and its associated pollution) increases when firms become more symmetric, since the incumbent seeks to deter the entry of a tough competitor. By contrast, when priors are low, an uninformative equilibrium arises where overproduction (and pollution) shrinks as firms are relatively symmetric, given that the incumbent reduces its mimicking efforts.

From a policy perspective, our results suggest that, if environmental regulation is accompanied by policies that reduce the production costs of polluting firms, the welfare benefits from regulation in the incomplete and complete information setting are very similar when priors are high. In this case, our measurement of the welfare benefits of regulation can hence overlook the information context in which firms interact without making large estimation errors. When priors are low, however, the combination of environmental regulation and cost-reducing policies shrinks the welfare benefits of regulation in the incomplete information game, pushing these benefits below those in the complete information setting. Therefore, ignoring the information context where the industry operates can, in this case, lead to an overestimation of the welfare benefits of the EPA's role. Our findings also suggest that environmental protection agencies can manage the distribution of information to potential entrants in order to improve social welfare. This case describes settings where the imposition of emission fees is politically unpopular and, hence, environmental policy is confined to the strategic dissemination of information. In particular, when priors are high, we demonstrate that the distribution of information is welfare-improving. When priors are low, however, the EPA might strategically conceal information from potential entrants in order to increase social welfare, especially when firms are relatively symmetric in their cost structure.

Related literature. This paper relates to the literature of environmental policy under uncertainty. Specifically, Weitzman (1974),[4] Roberts and Spence (1976), Farrell (1987), Segerson (1988), and Xepapadeas (1991) discuss the inefficiencies produced by environmental regulation when the policymaker is uninformed about firms' cost structure. Our model also analyzes a context of incomplete information but, unlike the previous papers, we focus on settings where the regulator has relatively accurate information about the incumbent's costs while the potential entrant is un-

[4] Stavins (1996) expands on Weitzman's paper allowing for correlation between benefit and cost uncertainty.

informed.[5] This study contributes to the above literature by analyzing a context where regulator and incumbent have interacted for long periods and, therefore, the regulator's information is more accurate than that of the potential entrant. We examine the welfare benefit of environmental regulation and, in particular, investigate under which conditions the role of the regulator can actually be more welfare-improving under incomplete than under complete information.

Standard entry-deterrence models, such as Milgrom and Roberts (1982), Harrington (1986), and Ridley (2008), consider industries where the incumbent's production does not generate negative externalities and, hence, ignore the role of the government in correcting this inefficiency. Our paper, in contrast, examines industries where these externalities are present and compares the welfare benefits of regulation under different information contexts. In addition, we also consider the informative effects of two signals, emission fees and output, as Milgrom and Roberts (1986) who analyze a model of entry deterrence where the informed firm uses two signals, price and advertising, to convey the quality of its product to consumers. Similarly, Harrington (1987) and 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 hide their type from the entrant. Likewise, we demonstrate that the presence of regulator hinders the incumbent's ability to conceal information from the uninformed entrant.

The following section describes the model under complete information, as well as the welfare benefits from environmental regulation in this context. Section 3 introduces incomplete information, where we separately consider the case of high and low priors, measuring for each of them the welfare benefits arising from regulation. Section 4 compares the welfare benefits under different information contexts, and discusses the policy implications of our equilibrium results. Finally, section 5 concludes.

2 Complete information

Let us examine an entry game where a monopolist incumbent is initially operating and an entrant must decide whether or not to join the market. In addition, consider a regulator who sets an emission fee per unit of output at every stage of the game. The incumbent's constant marginal costs are either high H or low L, i.e., $1 > c_{inc}^{H} > c_{inc}^{L} \geq 0$, where subscript *inc* denotes the incumbent. This section analyzes the case where all players are informed about the incumbent's marginal cost, while section 3 examines the setting in which the entrant is unable to observe such a cost. We study a two-stage game where, in the first stage, the regulator selects an emission fee t_1 and the monopolist responds by choosing an output level q. The inverse market demand is

[5] Barigozzi and Villeneuve (2006) also consider a a regulator who is informed about the health benefits of a particular product, and a group of potential consumers who use tax policy to form beliefs about the product quality. Since their study does not analyze an entry-deterrence model, however, tax policy cannot affect entry patterns in the industry.

$P(q) = 1 - q$. Thus, for a given fee t_1, the incumbent maximizes profits by solving,

$$\max_{q} \ (1-q)q - (c_{inc}^{K} + t_1)q$$

where $K = \{H, L\}$ denotes the incumbent's type. In the second stage, a potential entrant decides whether or not to join. 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 the entrant, respectively. Otherwise, the incumbent maintains its monopoly power during both periods. In addition, the entrant's marginal cost, c_{ent}, coincides with that of the high-cost incumbent. The entrant must incur a fixed entry cost $F > 0$, which induces entry when the incumbent's costs are high, but deters it when they are low.[6] Finally, the regulator's social welfare function considers consumer and producer surplus, tax revenue, and the environmental damage from pollution, defined as $ED(X) \equiv d \times X^2$, where X denotes aggregate output.[7] For comparison purposes, we next describe output and emission fees in the subgame perfect equilibrium of the game.

Lemma 1 (Complete information). *In the first period, the regulator sets an emission fee* $t_1^K = (2d-1)\frac{1-c_{inc}^K}{1+2d}$, *where* $K = \{H, L\}$, *and the incumbent responds with a production function* $q^K(t_1) = \frac{1-\left(c_{inc}^K + t_1\right)}{2}$ *which, in equilibrium, entails the production of the socially optimal output* $q^K(t_1^K) = \frac{1-c_{inc}^K}{1+2d} \equiv q_{SO}^K$. *Entry only occurs when the incumbent's costs are high. In the second period, if entry does not ensue (NE), the regulator maintains fees at* $t_2^{K,NE} = t_1^K$, *and the incumbent responds with an output function* $x_{inc}^{K,NE}(t_2)$, *which coincides with* $q^K(t_1)$. *If entry occurs (E), the regulator sets a second-period fee* $t_2^{H,E} = (4d-1)\frac{1-c_{inc}^K}{2(1+2d)}$ *and* $t_2^{L,E} = \frac{A(1-c_{inc}^H)-B(1-c_{inc}^L)}{2A}$, *when the incumbent's costs are high and low, respectively, where* $A \equiv 1 + 2d$ *and* $B \equiv 2 - 2d$, *and firms respond producing* $x_i^{K,E}(t_2) = \frac{1-2c_i^K + c_j^K - t_2}{3}$ *where* $i = \{inc, ent\}$ *and* $j \neq i$.

Under monopoly, the regulator seeks to induce the socially optimal output level, $q_{SO}^K \equiv \frac{1-c_{inc}^K}{1+2d}$, which is decreasing in environmental damage, d, and in incumbent's costs, c_{inc}^K. Therefore, the tax t_1^K that induces this output level is increasing in d and decreasing in c_{inc}^K. In particular, note that when $d \leq 0.5$, the emission fee t_1^K collapses to zero. Since we analyze the effect of taxes on output and welfare, we hereafter focus on settings where the environmental damage satisfies $d > 0.5$ and, therefore, emission fees are positive. Upon entry, the regulator seeks to induce the same socially optimal output at the aggregate level, q_{SO}^K. Hence, emission fee $t_2^{K,E}$ is more stringent than that under monopoly, i.e., $t_2^{K,E} > t_2^{K,NE}$, since aggregate output under duopoly is more distant to the social optimum; as in Buchanan (1969).[8]

[6] Note that if, in contrast, entry is independent of the incumbent's costs, the monopolist cannot use its first-period output as an informative signal to deter entry. Since we study the informative content of first-period actions (output and emission fees) and their consequences on social welfare, we hereafter consider that entry is only profitable when the incumbent's costs are high.

[7] A marginal increase in output, hence, entails a positive and increasing environmental damage, i.e., pollution is convex in output.

[8] Fee $t_2^{K,E}$ and the resulting duopoly output for both firms are positive as long as firms' costs are not extremely

The introduction of environmental policy hence induces the socially optimal level of pollution and, as a consequence, increases social welfare. The following proposition analyzes the welfare benefit from environmental regulation, measured by the difference $WB_{CI}^{K} \equiv W_{CI}^{K,R} - W_{CI}^{K,NR}$, which compares the social welfare with regulation, $W_{CI}^{K,R}$, and without regulation, $W_{CI}^{K,NR}$, where subscript CI denotes a complete information setting, and superscript R (NR) refers to regulation (no regulation, respectively).

Proposition 1. *In a context of complete information, the presence of a regulator yields welfare benefits of*

$$WB_{CI}^{L} = \frac{(1-2d)^2(1+\delta)(1-c_{inc}^{L})^2}{8(1+2d)} \quad \text{and} \quad WB_{CI}^{H} = \frac{\left[9(1-2d)^2 + 4(1-4d)^2\delta\right](1-c_{inc}^{H})^2}{72(1+2d)}$$

for the low- and high-cost incumbent, respectively, where δ denotes the discount factor. Both WB_{CI}^{L} and WB_{CI}^{H} are increasing in environmental damage, d.

Figure 1a below depicts equilibrium welfare levels $W_{CI}^{L,R}$ and $W_{CI}^{L,NR}$ for the low-cost incumbent, as well as the welfare benefit from having a regulator, $WB_{CI}^{L} \equiv W_{CI}^{L,R} - W_{CI}^{L,NR}$ in the shaded area; figure 1b illustrates similar welfare levels for the high-cost incumbent. For simplicity, we consider parameter values $\delta = 1$, $c_{inc}^{L} = 1/4$ and $c_{inc}^{H} = 1/2$.[9] Both figures show that the welfare benefit from regulation increases in the environmental damage, d. Hence, the presence of the regulator becomes more welfare improving when pollution is more damaging.[10]

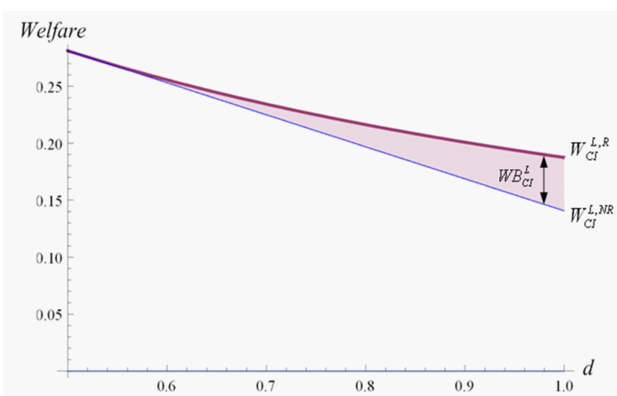

Figure 1a. Low-cost incumbent.

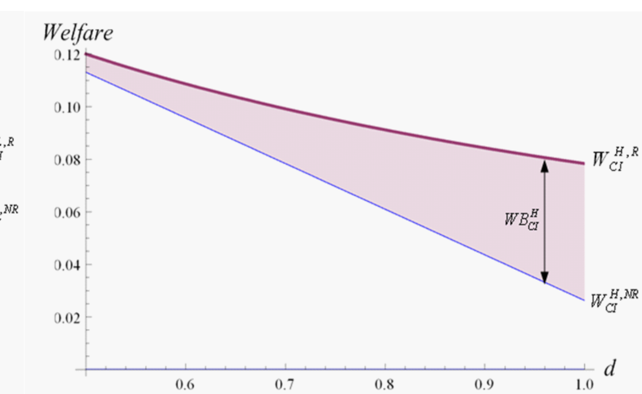

Figure 1b. High-cost incumbent.

different, i.e., $c_{inc}^{L} < c_{inc}^{H} < \frac{1+2dc_{inc}^{L}}{A}$, as described in the proof of lemma 1.

[9] In addition, we consider a fixed entry cost of $F = 0.005$, which guarantees entry only when the incumbent's costs are high. Specifically, F exceeds the entrant's duopoly profits when competing against a low-cost incumbent, $\frac{(1-d)^2}{16A^2}$, but lies below its duopoly profits when facing a high-cost incumbent, $\frac{1}{16A^2}$, for all admissible values of $d \in \left(\frac{1}{2}, 1\right)$. Other parameter combinations yield similar results and can be provided by the authors upon request.

[10] In addition, note that both welfare benefits are decreasing in firms' production costs, i.e., WB_{CI}^{K} decreases in c_{inc}^{K}.

In the following section, we investigate the welfare benefits from introducing environmental regulation in settings where the entrant cannot observe the incumbent's cost structure before joining the industry. Section 4 then evaluates whether the welfare benefits from regulation are larger in the complete or incomplete information environment.

3 Incomplete information

In this section we examine 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 its 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 responds choosing its 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 $\mu(c^H_{inc}|q(t_1), t_1)$ denote the entrant's posterior belief that the incumbent's costs are high. Given these beliefs, the entrant decides whether or not to enter the industry.[11]

4. 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, $x^{K,NE}_{inc}(t_2^{K,NE})$. 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 $x^{K,E}_{inc}(t_2^{K,E})$ and $x^{K,E}_{ent}(t_2^{K,E})$.[12]

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 Lemma 2 in the appendix). The high-cost incumbent selects a complete information first-period profit-maximizing output function, $q^H(t_1)$, for any first-period tax t_1. It 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 the overall profits from selecting $q^H(t_1)$ are greater than those from deviating, that is

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

[11] As described in the previous section, when the incumbent's costs are low, the entrant finds entry unprofitable whereas, when they are high, entry is profitable. Denoting, for compactness, D^K_{ent} the entrant's duopoly profits in equilibrium under a tax $t_2^{K,E}$ when the entrant faces a K-type incumbent, this implies that $D^L_{ent} < F < D^H_{ent}$.

[12] Step 4, 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 1-3.

where $\delta \in (0,1]$ represents the firm's discount factor, $M^H_{inc}(q(t_1), t_1)$ denotes the incumbent's first-period monopoly profits for any output function $q(t_1)$ and fee t_1, $D^H_{inc} \equiv \frac{\left(1-c^H_{inc}\right)^2}{4(1+2d)}$ is the incumbent's duopoly profits evaluated at the equilibrium fee $t_2^{H,E}$ (as described in lemma 1) and, similarly, $\overline{M}^H_{inc} \equiv \frac{\left(1-c^H_{inc}\right)^2}{1+2d}$ represents its 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

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

where $\overline{M}^L_{inc} \equiv \frac{\left(1-c^L_{inc}\right)^2}{1+2d}$, $M^L_{inc}(q^L(t_1), t_1) \equiv \frac{\left(1-c^L_{inc}-t_1\right)^2}{4}$ and D^L_{inc} represents duopoly profits, i.e., $D^L_{inc} \equiv \frac{\left[1+Ac^H_{inc}-2(1+d)c^L_{inc}\right]\left[3+Ac^H_{inc}-2(2+d)c^L_{inc}\right]}{12A^2}$. Thus, conditions C1-C2 guarantee the high-cost incumbent does not have incentives to mimic the output decision of the low-cost firm.

The next subsection focuses on equilibrium outcomes when the prior probability, p, is relatively high, showing that only "informative" equilibria can be sustained, where the entrant can infer the incumbent's costs. Subsection 3.2 then analyzes equilibrium behavior when priors are low, demonstrating that, in this setting, an "uninformative" equilibrium can be supported where the entrant is unable to infer the incumbent's type after observing the regulator's and incumbent's choices. Importantly, we demonstrate that the regulator anticipates both firms' strategic behavior in subsequent stages and, as a consequence, can design a tax policy in the signaling game that induces the socially optimal output.

3.1 High priors

The following proposition shows that the only strategy profile that can be sustained as an informative Perfect Bayesian Equilibrium (PBE) implies that the regulator selects a type-dependent tax level[13] and the incumbent responds with a type-dependent output function. Therefore, the output level produced by the high- and low-cost firms differs, allowing for information transmission regarding the incumbent's type. In addition, only the least-costly equilibrium (entailing the smallest deviation from complete information strategies) survives the Cho and Kreps' (1987) Intuitive Criterion, which allows for a unique equilibrium prediction.[14]

[13] 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.

[14] Note that the entrant could also infer accurate information about the incumbent's cost structure in the following strategy profiles. First, if the regulator chooses a type-dependent tax level and both types of incumbent use the same output function, the output level that the entrant ultimately observes differs between the high- and low-cost incumbent, allowing the entrant to deduce the incumbent's production costs. Similarly, if the regulator sets a type-independent tax level while the incumbent selects a type-dependent output function, the entrant can also infer the incumbent's type. However, none of these strategy profiles can be supported as a PBE, as shown in Espinola-Arredondo et al. (2011). Intuitively, in the first strategy profile, the high-cost incumbent would attract entry by selecting a type-independent output function. Conditional on entry, it obtains a larger profit deviating to the type-dependent output function $q^H(t_1)$. Likewise, in the second strategy profile, the entrant joins the market after observing the type-independent fee t_1 and output level $q^H(t_1)$. Hence, conditional on entry, the regulator facing the high-cost incumbent can increase social welfare by deviating to the type-dependent fee t_1^H.

Lemma 2. *An informative equilibrium can be sustained when priors satisfy* $p > \overline{p} \equiv \frac{F-D^L_{ent}}{D^H_{ent}-D^L_{ent}}$, *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 its costs are high and low, respectively, where*

$$t_1^A \equiv \frac{\left(1-c^H_{inc}\right)\left[A+\sqrt{3\delta}\right]-2(1-c^L_{inc})}{A} \quad \text{and} \quad q^A(t_1) \equiv \frac{\left(1-c^H_{inc}\right)\left[A+\sqrt{3\delta}\right]}{2A} - \frac{t_1}{2}.$$

The entrant responds by 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* $q^A(t_1) > q^L(t_1)$ *if costs satisfy* $c^H_{inc} < \frac{\sqrt{3\delta}+Ac^L_{inc}}{\sqrt{3\delta}+A} \equiv \widehat{\rho}$*, and emission fee* t_1^A *induces the socially optimal output* q^L_{SO} *by solving* $q^L_{SO} = q^A(t_1)$*.*

The low-cost incumbent hence selects an output function $q^A(t_1)$ higher than under complete information, $q^L(t_1)$, in order to reveal its efficient cost structure 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^L_{SO} by solving $q^L_{SO} = q^A(t_1)$; as depicted in figure 2 below. Therefore, the efficient output level —sustained under complete information settings with fee t_1^L— can also be induced in the informative equilibrium by the more stringent fee $t_1^A > t_1^L$.[15] Hence, the entrant observes a first-period output q^L_{SO}, as under complete information, but a higher tax t_1^A, which implies that the incumbent must be using output function $q^A(t_1)$ and thus it exerts a separating effort to convey its type.

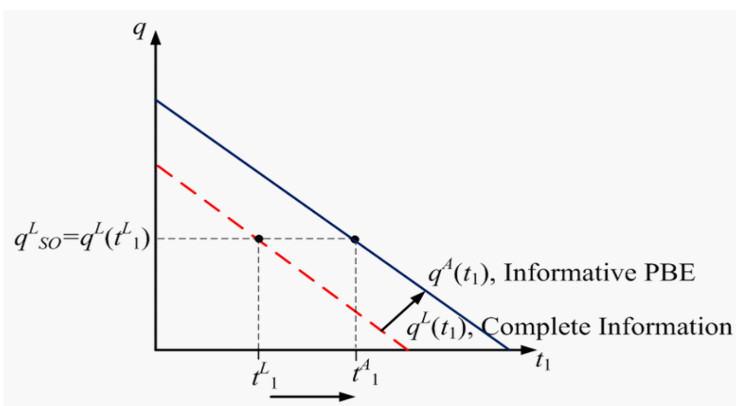

Figure 2. Informative PBE.

Since the regulator induces the production of the socially optimal output, both under complete information and in the informative equilibrium, social welfare is the same in both information settings. The introduction of regulation in the informative equilibrium, however, can yield larger welfare benefits than under complete information. As in the previous section, let us next measure

[15] In addition, note that the low-cost incumbent finds it profitable to separate from its complete-information output function in order to deter entry only if the potential entrant is relatively efficient, i.e., competition in the post-entry game would be "tough," as indicated by condition $c^H_{inc} < \widehat{\rho}$. This conditions guarantees that output function $q^A(t_1)$ lies above $q^L(t_1)$ in figure 2.

these welfare benefits using the difference $WB^{L}_{HighPriors} \equiv W^{L,R}_{HighPriors} - W^{L,NR}_{HighPriors}$, which compares social welfare with and without regulation when priors are high, $p > \overline{p}$, and, thus, agents behave as prescribed in the informative equilibrium.

Proposition 2. *When priors are high, the presence of the regulator in the incomplete information game entails a welfare benefit, measured by* $WB^{L}_{HighPriors} \equiv W^{L,R}_{HighPriors} - W^{L,NR}_{HighPriors}$ *when the incumbent's costs are low, which is strictly positive for all parameter values. When the incumbent's costs are high, the welfare benefit is* $WB^{H}_{HighPriors} \equiv W^{H,R}_{HighPriors} - W^{H,NR}_{HighPriors}$*, which coincides with that under complete information,* WB^{H}_{CI}*, for all parameter values.*

Under no regulation, the low-cost incumbent increases its first-period output, relative to complete information, in order to signal its type to potential entrants. Such overproduction hence generates more pollution than in complete information contexts, which suggests that an additional form of inefficiency emerges in the incomplete information setting, implying that the regulator's task becomes more beneficial in this context. (Section 4 confirms this result by comparing the welfare benefits of regulation in the incomplete information game, $WB^{L}_{HighPriors}$, and in its complete information version, WB^{L}_{CI}).

Finally, when the incumbent's costs are high, regulation yields the same welfare level as under complete information, i.e., $W^{H,R}_{HighPriors} = W^{H,R}_{CI}$, since, as described in lemma 2, incumbent and regulator's actions coincide in both information contexts. Similarly, when the regulator is absent, the incumbent's production is the same in both information settings; hence, $W^{H,NR}_{HighPriors} = W^{H,NR}_{CI}$. Therefore, the welfare benefits satisfy $WB^{H}_{HighPriors} = WB^{H}_{CI}$, which are strictly positive.[16]

Comparative statics. Let us next examine the comparative statics behind our equilibrium results. The figure below illustrates how the welfare benefits of introducing a regulator change as the cost-differential increases.

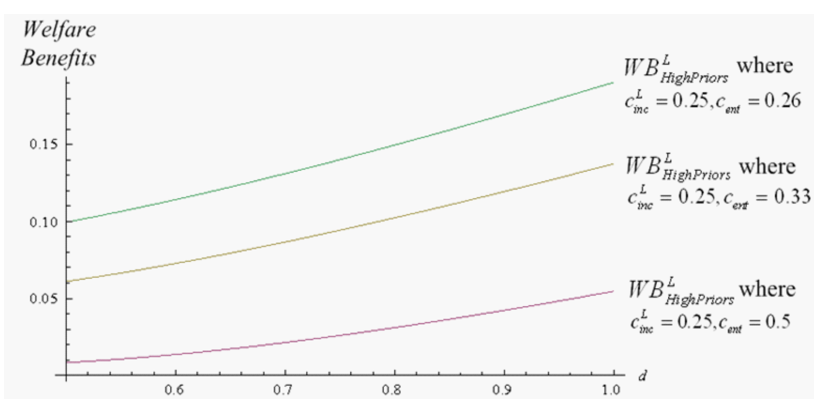

Figure 3. Effects of c^{H}_{inc} on $WB^{L}_{HighPriors}$.

[16] Hence, the graphical representation of the welfare benefit from introducing regulation for the high-cost incumbent, $WB^{H}_{HighPriors}$, coincides with that in figure 1b for the complete information game, WB^{H}_{CI}.

Specifically, when the cost-differential between the incumbent and entrant is small, e.g., $c_{inc}^{L} = 0.25$ and $c_{ent} = 0.26$, the low-cost firm is threatened by a though potential competitor, since the entrant's marginal costs are close to those of the incumbent. In this setting, the incumbent is willing to substantially overproduce in order to reveal its type and avoid entry. Such overproduction, however, entails more pollution and, therefore, the presence of the regulator yields higher welfare benefits; as depicted in the highest curve of figure 3.[17] In contrast, when the cost-differential is large, e.g., $c_{inc}^{L} = 0.25$ and $c_{ent} = 0.5$, the incumbent enjoys a cost advantage relative to the entrant. Since the incumbent, hence, does not feel threatened, it does not exert a strong separating effort in order to reveal its type, thus generating lower levels of pollution. The regulator's task, therefore, becomes less necessary when the firms' cost differential is large, as illustrated in the lowest $WB_{HighPriors}^{L}$ curve in figure 3. The next figure represents the effect of different discount factors on the welfare benefits from regulation

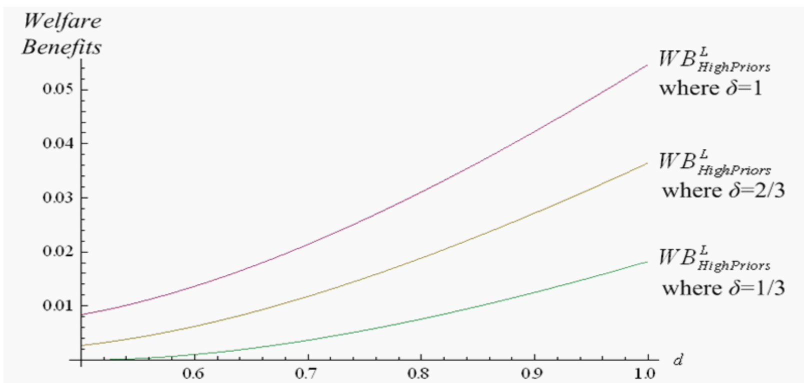

Figure 4. Effects of δ on $WB_{HighPriors}^{L}$

Figure 4 demonstrates that an increase in the discount factor produces an upward shift in the welfare benefits from regulation, $WB_{HighPriors}^{L}$. Intuitively, when the discount factor is close to one, future monopoly benefits become more important. Hence, the unregulated low-cost incumbent is willing to overproduce in order to reap the future profits from deterring entry, generating, as a consequence, more pollution. The regulator's presence, therefore, entails a larger welfare benefit. A converse argument applies when the discount factor is low, e.g., $\delta = 1/3$. In this setting, the incumbent assigns a low value to the future monopoly profits from deterring entry, thus reducing its incentives to overproduce in order to reveal its type. Therefore, the welfare benefits from regulation are small.

[17] In order to interpret the relative size of these welfare benefits, note that the low-cost incumbent's monopoly profits are $\frac{(1-c_{inc}^{L})^2}{1+2d}$. In our parametric example where $c_{inc}^{L} = 0.25$, this implies that monopoly profits range from 0.26 when $d = 1/2$ to 0.17 when $d = 1$. Therefore, when the environmental damage from pollution, d, is relatively high and the cost differential among firms is small, introducing environmental regulation yields welfare benefits which are similar in size to the profits of an efficient incumbent.

3.2 Low priors

In this subsection, we examine equilibrium behavior where priors are sufficiently low, $p \leq \bar{p}$. For simplicity, we hereafter focus on the case where $\delta \geq 1/2$, implying that the incumbent assigns a sufficiently large weight to future profits, thus making the threat of entry relevant. When the regulator is absent, standard entry-deterrence models predict that the high-cost incumbent mimics the production decision of the low-cost firm, in order to be perceived as an efficient firm, and thus deter entry. The following lemma shows that, in the presence of environmental regulation, such entry-deterring practice can only be exercised under a more restrictive set of parameter conditions.

Lemma 3. *When priors are sufficiently low, $p \leq \bar{p}$, an uninformative PBE can be sustained where the regulator selects a type-independent emission fee t_1^L, both types of incumbent choose output function $q^L(t_1)$, and entry does not ensue, if production costs satisfy $c_{inc}^H < \frac{\sqrt{2A}+2Ac_{inc}^L}{2A+\sqrt{2A}} \equiv \bar{\rho}$.*

Intuitively, an uninformative strategy profile requires both an overtaxation from the regulator (who sets a fee $t_1^L > t_1^H$ to the high-cost incumbent mimicking the fee for the low-cost firm), and an overproduction from the high-cost incumbent, who chooses an output function $q^L(t_1)$ in order to mimic the output decision of the low-cost firm. Ultimately, this strategy profile entails the production of output level $q^L(t_1^L) = q_{SO}^L$, rather than the socially optimal output q_{SO}^H that arises under complete information; as depicted in figure 5 below.

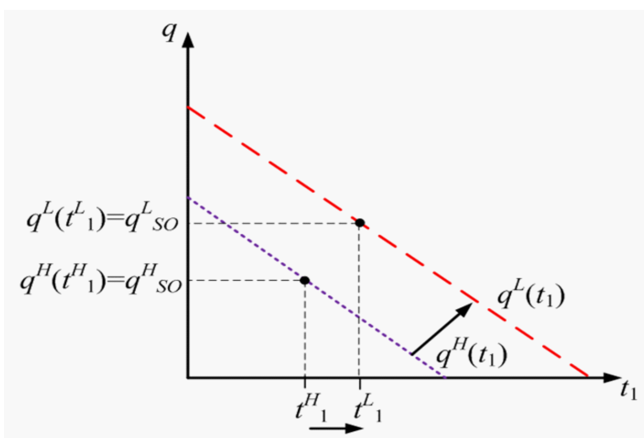

Figure 5. Uninformative PBE.

Overtaxation, on one hand, entails a first-period welfare loss measured by $\frac{(c_{inc}^H - c_{inc}^L)^2}{2\delta(1+2d)}$ in our setting (see proof of lemma 3 for details), which is increasing in the cost-asymmetry between firms, since the difference between t_1^H and t_1^L enlarges. On the other hand, overtaxing the incumbent deters entry, yielding a second-period welfare gain, due to savings in the fixed entry cost F. In particular, the regulator designs second-period emission fees to induce output level q_{SO}^H independent of the entry decision.[18] This entails that second-period welfare when entry is deterred is larger than

[18] Specifically, if entry does not ensue, the regulator chooses a fee $t_2^{H,NE} = t_1^H$, which induces the socially optimal

when entry ensues, given the savings in the entry cost. Hence, when the first-period welfare loss from overtaxation is offset by the second-period welfare gain from deterring entry, the regulator behaves as prescribed in the uninformative equilibrium, which occurs when the cost differential is sufficiently low, i.e., $c_{inc}^H < \overline{\rho}$.[19] In addition, the high-cost incumbent mimics the output decision of the low-cost firm if its cost "disadvantage" is not very strong, $c_{inc}^H < \overline{\rho}$. In this case, the second-period monopoly profits that the incumbent obtains from deterring entry outweigh the costs that this firm incurs by overproducing. Ultimately, the actions of both incumbent and regulator help the former conceal its type from the potential entrant, who stays out given its low priors.

Let us next compare entry deterrence with and without regulator. When the regulator is absent, the uninformative equilibrium can be sustained if the costs of the high-type incumbent satisfy $c_{inc}^H < \frac{5\delta-3(1-c_{inc}^L)\sqrt{5\delta}-9c_{inc}^L}{5\delta-9} \equiv \rho$,[20] whereas when the regulator is present this equilibrium can be supported under more restrictive conditions, since $c_{inc}^H < \overline{\rho} < \rho$. Therefore, environmental policy hinders the incumbent's ability to practice entry deterrence. Intuitively, the regulator's overtaxation makes the incumbent's overproduction effort more costly, thus shrinking the set of costs under which this firm practices entry deterrence. The following proposition evaluates the welfare benefits from introducing environmental regulation in this information context.

Proposition 3. *When priors are low, the presence of the regulator in the incomplete information game entails a welfare benefit, measured by* $WB_{LowPriors}^H \equiv W_{LowPriors}^{H,R} - W_{LowPriors}^{H,NR}$ *when the incumbent's costs are high, which is strictly positive for all parameter values. When the incumbent's costs are low, the welfare benefit is* $WB_{LowPriors}^L \equiv W_{LowPriors}^{L,R} - W_{LowPriors}^{L,NR}$*, which coincides with that under complete information,* WB_{CI}^L*, for all parameter values.*

Standard entry-deterrence models, where the regulator is absent, as Milgrom and Roberts (1982), prescribe that the high-cost incumbent mimics the output function of the low-cost firm (overproduces) in order to conceal its type from the potential entrant and, thus, avoid entry. This overproduction yields a pollution level above the social optimum, thereby generating a large environmental damage during the first-period game. When the regulator is present, however, his overtaxation reduces the incumbent's production thus decreasing environmental damage. In the second period, the environmental damage from pollution is not internalized when the regulator is absent, while it is when he is present. Therefore, environmental policy yields a larger social welfare both in the first and second period, thus entailing a positive welfare benefit $WB_{LowPriors}^H > 0$.[21] Fig-

output q_{SO}^H. Similarly, if entry occurs, the regulator selects a tax $t_2^{H,E}$ which also induces output q_{SO}^H.

[19] More formally, the regulator selects t_1^L when the first-period welfare loss from overtaxation is smaller than the entry cost, i.e., $\frac{(c_{inc}^H - c_{inc}^L)^2}{2\delta(1+2d)} < F$. This condition is, however, only compatible with the assumption of profitable competition against the high-cost incumbent, $D_{ent}^L < F < D_{ent}^H$, if $\frac{(c_{inc}^H - c_{inc}^L)^2}{2\delta(1+2d)} < D_{ent}^H$, which holds when $c_{inc}^H < \overline{\rho}$.

[20] When the regulator is absent, our model resembles that of standard entry-deterrence games, as Milgrom and Roberts (1982). For more details about the uninformative equilibrium without regulation, see Appendix 1.

[21] When the incumbent's costs are low, the actions of both regulator and incumbent coincide with those under

ure 6 describes how the welfare benefits from introducing environmental regulation, $WB^{H}_{LowPriors}$, are affected by changes in this firm's production costs.

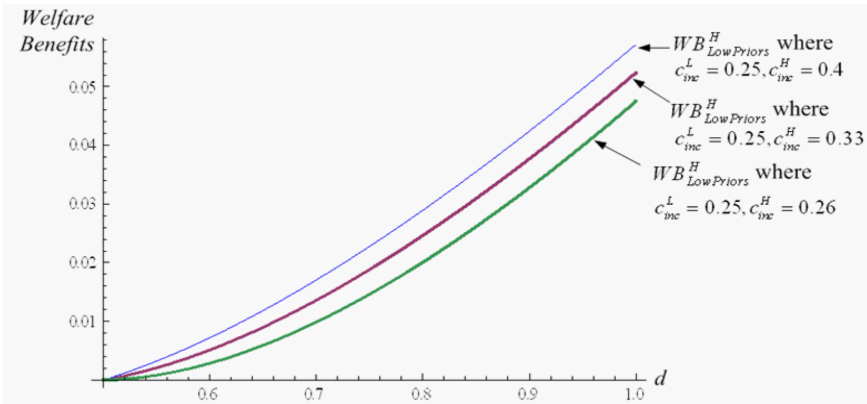

Figure 6. Effects of c^{H}_{inc} on $WB^{H}_{LowPriors}$

Unlike our results regarding the welfare benefits of regulation when priors are high (figure 3), an increase in the cost differential between the low- and high-cost incumbent produces an upward shift in the welfare benefits associated with having a regulator. Intuitively, when the regulator is absent, an equilibrium can be sustained in which the high-cost incumbent chooses to increase its output in order to mimic the low-cost firm, and deter entry. As this cost differential increases, the inefficient firm must increase the extent of its overproduction, thus entailing a larger pollution. The regulator's task, therefore, becomes more necessary in this setting, shifting $WB^{H}_{LowPriors}$ upwards. If, in contrast, the costs of the high- and low-cost incumbent are relatively similar, the inefficient firm does not need to substantially increase its output level in order to mimic the output decision of the efficient firm, generating a small increase in pollution and, hence, the benefits from introducing environmental regulation decline.[22]

4 Welfare comparisons

Let us now examine whether the welfare benefits of regulation, despite being positive in both information contexts, are larger under complete or incomplete information settings.

Proposition 4. *The welfare benefit from environmental regulation under incomplete information is larger than that under complete information when priors are high. That is,*

$$W^{K,R}_{HighPriors} - W^{K,NR}_{HighPriors} \geq W^{K,R}_{CI} - W^{K,NR}_{CI}$$

complete information, which holds both when the regulator is present and when he is absent. We, therefore, focus on equilibrium behavior when the incumbent's costs are high.

[22] Similarly as in contexts where priors are high, an increase in the discount factor produces an upward shift on the welfare benefits from regulation; as described in figure 4.

for any incumbent's costs $K = \{H, L\}$. When priors are low, in contrast, the welfare benefit from environmental regulation under complete information is larger than that under incomplete information.

First, note that when priors are relatively high, the informative equilibrium emerges and the regulator designs environmental policy to induce the socially optimal output, q_{SO}^{L}, both under complete and incomplete information, thus entailing the same social welfare, i.e., $W_{HighPriors}^{L,R} = W_{CI}^{L,R}$, as depicted in figure 7.[23]

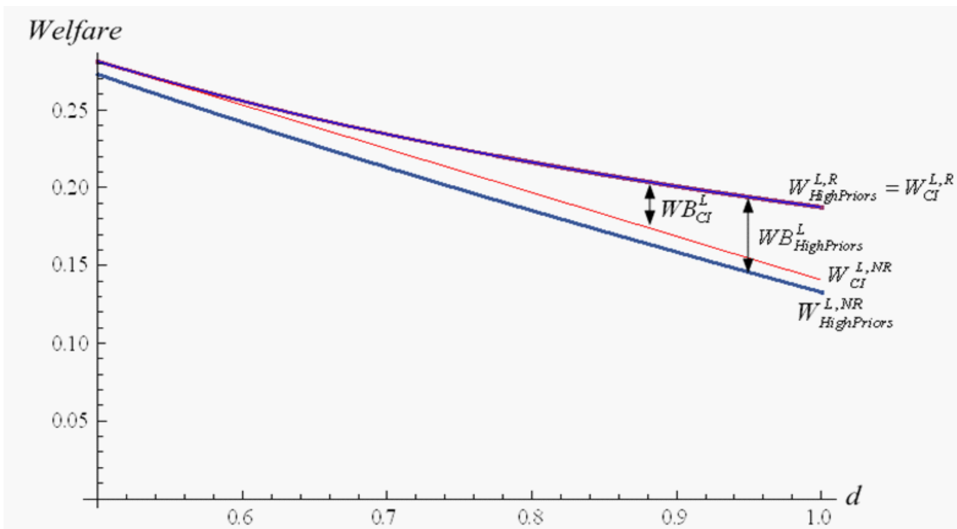

Figure 7. Comparison of WB under high priors.

However, under no regulation, social welfare does not coincide in both information contexts. Specifically, in the informative equilibrium, the low-cost incumbent exerts a separating effort (relative to complete information) in order to reveal its type and deter entry. When the regulator is absent, such an overproduction entails a larger environmental damage than in complete information contexts. Intuitively, under complete information an inefficiency exists, arising from the fact that firms do not internalize the external effects from pollution. Under incomplete information, such inefficiency is emphasized by the incumbent's overproduction, thus decreasing social welfare, and making regulation more beneficial under incomplete than complete information, i.e., $W_{HighPriors}^{L,R} - W_{HighPriors}^{L,NR} \geq W_{CI}^{L,R} - W_{CI}^{L,NR}$, as figure 7 illustrates.

Furthermore, such difference-in-difference, $\left(W_{HighPriors}^{L,R} - W_{HighPriors}^{L,NR}\right) - \left(W_{CI}^{L,R} - W_{CI}^{L,NR}\right)$, enlarges when the cost differential $(c_{ent} - c_{inc}^{L})$ decreases; as illustrated in figure 8. Intuitively, when both types of firms experience similar production costs, the low-cost incumbent faces a tough competitor it seeks to deter. Hence, the incumbent increases its overproduction in order to convey its

[23] For consistency with our previous examples, the figure considers the same parameter combination $\delta = 1$, $c_{inc}^{H} = 1/2$ and $c_{inc}^{L} = 1/4$.

type to the potential entrant, generating more pollution, thus making the regulator's role more welfare improving; as represented by the highest curve of figure 8.

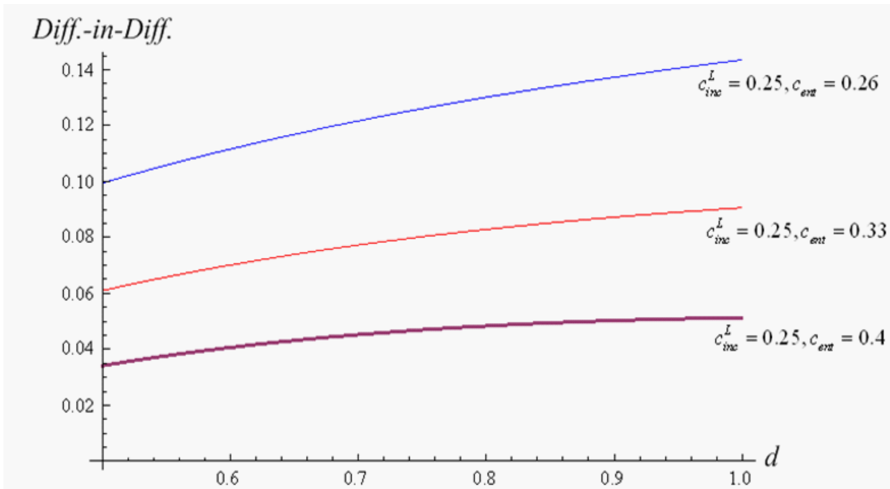

Figure 8. Diff-in-Diff. with high priors.

Unlike the case of high priors, the presence of the regulator does not guarantee the production of the socially optimal output when priors are low. Specifically, overtaxation and overproduction yield an output level $q^L(t_1^L) = q_{SO}^L$, above the socially optimal level for the high-cost incumbent, q_{SO}^H. Under complete information, in contrast, environmental policy achieves a socially optimal output across both periods, yielding a larger social welfare, $W_{CI}^{H,R} > W_{LowPriors}^{H,R}$; as depicted in figure 9a below. When the regulator is absent, each information context also yields a different welfare result. In particular, the practice of entry deterrence by the high-cost incumbent produces a first-period negative effect and a second-period positive effect on welfare. On one hand, the negative effect stems from the incumbent's overproduction in order to mimic the low-cost firm, yielding a larger pollution level than under complete information.[24] On the other hand, the incumbent's entry deterrence causes a positive effect since only the monopoly output is produced in the second-period game, which yields a lower pollution level than under complete information, where a duopoly market operates. When the high-cost incumbent is relatively efficient,[25] it exerts a small mimicking effort, and the positive effect offsets the negative effect, i.e., $W_{LowPriors}^{H,NR} > W_{CI}^{H,NR}$, as depicted in figure 9a. If, instead, the high-cost incumbent is relatively inefficient, it exerts a large mimicking effort, which implies that $W_{LowPriors}^{H,NR} < W_{CI}^{H,NR}$. However, note that this firm cannot be extremely inefficient, since otherwise the uninformative equilibrium would not exist. Thus, $W_{LowPriors}^{H,NR}$ does not lie substantially below $W_{CI}^{H,NR}$ under any combination of parameter values. As a consequence, welfare

[24] A given increase in first-period output produces a positive effect, due to a larger consumer surplus, but it also generates a negative effect, since pollution increases environmental damage. Given that $d > 0.5$, the negative dominates the positive effect, entailing an overall negative effect on first-period welfare.

[25] For more details about the cost cutoff for which social welfare in the complete information game exceeds that under incomplete information, see proof of Proposition 4.

benefit WB^H_{CI} is still larger than $WB^H_{LowPriors}$, i.e., the difference in welfare benefits $WB^H_{LowPriors} - WB^H_{CI}$ is negative, but approaches zero when the high-cost incumbent becomes more inefficient, as shown in the highest curve in figure 9b. The welfare benefit of regulation is therefore larger under complete than incomplete information, i.e., $WB^H_{CI} > WB^H_{LowPriors}$, for all parameter values under which the uninformative equilibrium can be supported.

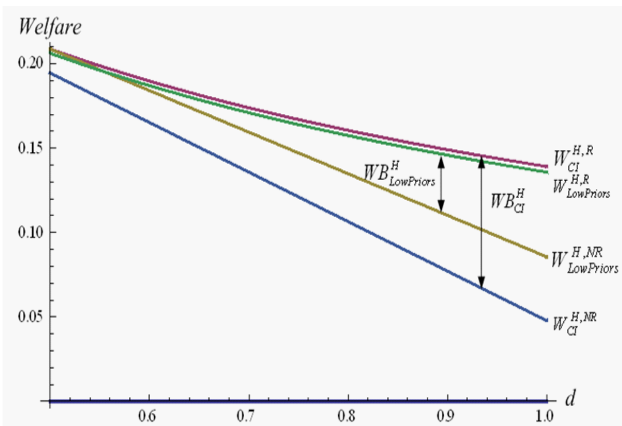

Figure 9a. Comparison of WB under low priors.

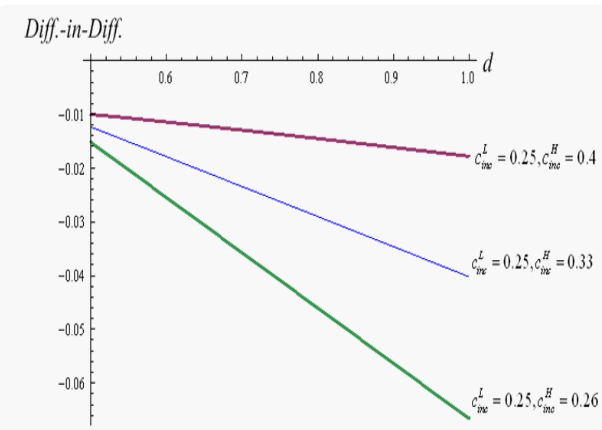

Figure 9b. Diff-in-Diff. with low priors.

Finally, note that the difference-in-difference $\left(W^{H,R}_{LowPriors} - W^{H,NR}_{LowPriors}\right) - \left(W^{H,R}_{CI} - W^{H,NR}_{CI}\right)$ can be intuitively understood as the estimation error that arises from measuring the welfare benefits of environmental regulation assuming a complete information context where, in fact, the industry operates in an incomplete information setting. (A similar argument is applicable for the case of high priors.) If such estimation error is positive, ignoring the incomplete information context where firms interact leads to an underestimation of the welfare benefit of introducing environmental policy; as observed in figure 8 where priors are high. By contrast, if such estimation error is negative, ignoring the incomplete information framework entails an overestimation of the benefits associated with environmental regulation; as depicted in figure 9b.

4.1 Discussion

Cost-reducing policies. Our results suggest that government policies aimed at reducing the production costs of polluting firms can entail extremely different welfare implications, depending on the information available to entrants and the industry characteristics. In particular, our conclusions in the informative equilibrium of section 3.1 demonstrate that a policy that helps the incumbent firm reduce its production costs, thus enlarging the cost differential relative to the entrant, leads it to behave more similarly to the complete information game. As a result, the welfare benefits of environmental regulation in this setting approach those of the complete information context. Therefore, when the cost differential among firms is relatively small, the regulator can essentially ignore the information context in which the industry operates, since the welfare benefits associated with his intervention are approximately the same. In contrast, when priors are relatively low, and the equilibrium outcomes in section 3.2 emerge, a reduction in the firms' cost differential implies a larger welfare benefit of environmental regulation under complete than under incomplete information settings. Unlike in the context where priors are high, programs that reduce the cost differential among firms make more relevant the consideration of the information available to firms that seek to enter the industry. Specifically, ignoring the information context where the industry operates can, in this case, lead to an overestimation of the welfare benefits associated with environmental protection agencies, such as the EPA in the United States.

An "almost inactive" EPA that only manages information. If emission fees are politically unattractive, the EPA can, nonetheless, strategically manage the information context in which the industry operates, by revealing or concealing the incumbent's cost structure to firms interested in entering the market. Our results suggest that, under high priors, the EPA should promote complete information, since a larger social welfare can be obtained in this case than under the informative equilibrium, i.e., $W_{CI}^{L,NR} > W_{HighPriors}^{L,NR}$. Intuitively, because the low-cost incumbent does not need to overproduce in order to convey its type to potential entrants, lower levels of pollution are generated, thus increasing social welfare. By contrast, when priors are relatively low, the EPA might strategically choose to conceal information about the incumbent's costs, depending on the cost differential between the incumbent and the entrant. Specifically, when the incumbent is relatively efficient, our results imply that the welfare that arises under incomplete information is larger than under complete information, $W_{LowPriors}^{H,NR} > W_{CI}^{H,NR}$, leading the regulator to conceal information from the entrant. If, in contrast, the incumbent is inefficient, then our above findings show that $W_{LowPriors}^{H,NR} < W_{CI}^{H,NR}$, inducing the regulator to reveal such information to the entrant. It is important to mention that the strategic dissemination of information by the EPA only serves as a second-best regulation. Indeed, it helps dissipate one form of inefficiency (overproduction in incomplete information settings) but does not eliminate the inefficiency that arises in complete information contexts, where the incumbent does not internalize the negative welfare effects of its production decision.

Firms' opposition to environmental regulation. Our results also predict that, despite the welfare properties of environmental policy in both information contexts, firms' profits decrease more significantly in incomplete than in complete information settings. Specifically, regulation becomes more stringent, both under high and low priors, ultimately reducing profits. As a consequence, we can anticipate firms to especially oppose environmental regulation when the agency has relatively accurate information after long periods of interaction with the incumbent while the potential entrant, in contrast, has access to less precise information. Our findings therefore predict that the threat of entry in industries that have been monopolized for several years leads the regulator to impose more stringent policies. His task nonetheless faces a stronger opposition by regulated firms, thus emphasizing the recurrent conflict between regulator and firms, and providing more incentives for firms to lobby against environmental policy reform.

5 Conclusions

This paper evaluates the welfare benefits of introducing environmental regulation in a monopolized market that is subject to the threat of entry, not only under complete information settings, but also under incomplete information contexts, where the entrant must use the regulator's tax policy and the incumbent's output decision to infer the incumbent's productivity. Under complete information, we identify an inefficiency arising from firms not internalizing the environmental externality they generate. Importantly, such inefficiency is emphasized in contexts of incomplete information, where the incumbent overproduces in order to convey its cost structure to potential entrants and thus deter entry, which occurs when priors are high, or to conceal it by mimicking the output decision of the efficient firm, when priors are low. Therefore, the welfare benefit of regulation in incomplete information contexts is generally larger than under complete information. In addition, our results also identify under which conditions an under- or over-estimation of the welfare benefits of environmental regulation arises from ignoring the information setting in which firms interact.

Our paper considers that the regulator has interacted with the incumbent for a relatively long period of time and, as a consequence, can infer its production costs more accurately than the potential entrant does. In some recently developed industries, however, the regulator lacks such extended interaction, and he is then as uninformed as the potential entrant. Such analysis would introduce additional layers of uncertainty into our entry-deterring game, since one more agent (the regulator) is uninformed. This setting would help us evaluate if one of the general findings in this paper —that the introduction of uncertainty leads to more inefficiencies and, thus, enlarges the welfare benefits from environmental regulation— is further intensified when more players are uninformed. Furthermore, we examine flow externalities, since the negative effects of pollution dissipate across periods. A natural extension, hence, would allow for first-period pollution to still impose negative effects on second-period welfare, thus inducing a more stringent regulation that accounts for these intertemporal effects.

6 Appendix

6.1 Appendix 1 - Unregulated high-cost incumbent

In the absence of environmental regulation, the high-cost incumbent is willing to mimic the low-cost firm, i.e., selecting a first-period output q^L, in order to deter entry if the following incentive compatibility condition holds

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

for the high-cost incumbent, and

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

for the low-cost firm. Specifically, note that output q^L and q^H in this context are not a function of emission fee t_1 since the regulator is absent. The incentive compatibility condition for the low-cost incumbent holds since by selecting q^L it deters entry, and q^L maximizes its first-period profits. The incentive compatibility condition of the high-cost firm, however, does not necessarily hold for all parameter values. In particular, the first-period monopoly profits that this incumbent obtains when selecting q^L are $M_{inc}^H(q^L) = \frac{(1-2c_{inc}^H+c_{inc}^L)(1-c_{inc}^L)}{4}$, whereas its monopoly profits when selecting q^H are $M_{inc}^H(q^H) = \frac{(1-c_{inc}^H)^2}{4}$. In the second period, if entry is deterred, this incumbent reaps monopoly profits of $\overline{M}_{inc}^H$, which coincide with $M_{inc}^H(q^H)$. If, in contrast, entry ensues, then the incumbent obtains duopoly profits of $D_{inc}^H = \frac{(1-c_{inc}^H)^2}{9}$. Hence, the high-cost incumbent's incentive compatibility condition holds if

$$\frac{\delta(1-c_{inc}^H)^2 + (1-2c_{inc}^H + c_{inc}^L)(1-c_{inc}^L)}{4} \geq \frac{(9+4\delta)(1-c_{inc}^H)^2}{36}$$

which implies that c_{inc}^H satisfies $c_{inc}^H < \frac{5\delta - 3(1-c_{inc}^L)\sqrt{5\delta} - 9c_{inc}^L}{5\delta - 9} \equiv \rho$. (Note that our parametric examples satisfy this condition since, for $\delta = 1$ and $c_{inc}^L = 1/4$, this cutoff becomes $c_{inc}^H < 0.57$.) Finally, the entrant cannot update its beliefs after observing q^L, and thus coincide with the prior probability $\mu(q^L) = p$, leading the entrant to stay out given that priors satisfy $p < \overline{p}$.

6.2 *Proof of Lemma 1*

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

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

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 $t_2^{H,E} = \frac{4d-1}{2}\frac{1-c_{inc}^H}{1+2d}$, 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 $c_{inc}^H < \frac{4d-1+Bc_{inc}^L}{A}$; as depicted in the figure below.

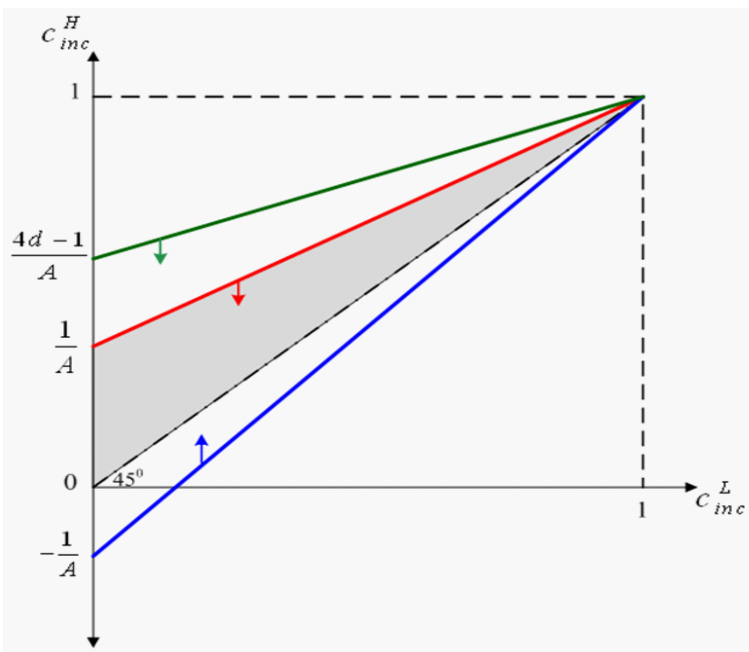

Figure A1. Production costs.

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., $c_{inc}^L < c_{inc}^H < \frac{1+2dc_{inc}^L}{A}$; as indicated in the shaded area of the figure. ■

6.3 *Proof of Proposition 1*

Low-cost incumbent. First-period social welfare when the regulator is present is

$$W_{1,CI}^{L,R} = \frac{1}{2}q^L(t_1^L)^2 + \left[1 - q^L(t_1^L)\right] q^L(t_1^L) - \left(c_{inc}^L + t_1^L\right) q^L(t_1^L) + t_1^L \times q^L(t_1^L) - d \times q^L(t_1^L)^2$$

where $q^L(t_1^L) = \frac{1-c_{inc}^L}{1+2d}$ and $t_1^L = (2d-1)\frac{1-c_{inc}^L}{1+2d}$. For the functional forms considered in the paper, $W_{1,CI}^{L,R} = \frac{(1-c_{inc}^L)^2}{2+2d}$. Second-period welfare, $W_{2,CI}^{L,R}$, coincides with first-period welfare, $W_{1,CI}^{L,R}$, since the incumbent keeps its monopoly power, and the regulator imposes a fee $t_2^{L,NE} = t_1^L$. Hence, overall social welfare is $W_{CI}^{L,R} = W_{1,CI}^{L,R} + \delta W_{2,CI}^{L,R}$, where δ denotes the regulator's discount factor. Then, $W_{CI}^{L,R} = \frac{(1+\delta)(1-c_{inc}^L)^2}{2+2d}$.

When the regulator is absent, i.e., $t_1^L = t_2^{L,NE} = 0$, first-period welfare is $W_{1,CI}^{L,NR} = \frac{(3-2d)(1-c_{inc}^L)^2}{8}$, and similarly for second-period welfare, $W_{2,CI}^{L,NR}$, since entry does not occur. Hence, overall social welfare is $W_{CI}^{L,NR} = W_{1,CI}^{L,NR} + \delta W_{2,CI}^{L,NR} = \frac{(1+\delta)(3-2d)(1-c_{inc}^L)^2}{8}$. Therefore, the welfare benefit from regulation is

$$WB_{CI}^L \equiv W_{CI}^{L,R} - W_{CI}^{L,NR} = \frac{(1-2d)^2(1+\delta)(1-c_{inc}^L)^2}{8(1+2d)}$$

which is increasing in d, since

$$\frac{\partial WB_{CI}^L}{\partial d} = \frac{(2d-1)(3+2d)(1+\delta)(1-c_{inc}^L)^2}{4(1+2d)^2}$$

is positive for all $d > 1/2$.

High-cost incumbent. First-period social welfare when the regulator is present is

$$W_{1,CI}^{H,R} = \frac{1}{2}q^H(t_1^H)^2 + \left[1 - q^H(t_1^H)\right] q^H(t_1^H) - \left(c_{inc}^H + t_1^H\right) q^H(t_1^H) + t_1^H \times q^H(t_1^H) - d \times q^H(t_1^H)^2$$

where $q^H(t_1^H) = \frac{1-c_{inc}^H}{1+2d}$ and $t_1^H = (2d-1)\frac{1-c_{inc}^H}{1+2d}$. For the functional forms considered in the paper, $W_{1,CI}^{H,R} = \frac{(1-c_{inc}^H)^2}{2+4d}$. Second-period welfare, $W_{2,CI}^{H,R}$, is

$$W_{2,CI}^{H,R} = \frac{1}{2}X^2 + PS(X) + T_2^{H,E} - d \times X^2$$

where $X = x_{inc}^{H,E}(t_2^{H,E}) + x_{ent}^{H,E}(t_2^{H,E})$, $PS(X) \equiv (1-X)X - \left(c_{inc}^H + t_2\right)X - F$, and $T_2^{H,E} \equiv t_2^{H,E}X$. Hence, $W_{2,CI}^{H,R} = \frac{(1-c_{inc}^H)^2}{2+4d} - F$, which coincides with $W_{1,CI}^{H,R}$ (except for the entry cost, F) given that the regulator induces the same socially optimal output q_{SO}^H in both periods. Therefore, overall social welfare is $W_{CI}^{H,R} = W_{1,CI}^{H,R} + \delta W_{2,CI}^{H,R} = \frac{(1+\delta)(1-c_{inc}^H)^2}{2+4d} - \delta F$. When the regulator is absent, first-period welfare is $W_{1,CI}^{H,NR} = \frac{(3-2d)(1-c_{inc}^H)^2}{8}$. The second-period welfare, $W_{2,CI}^{H,NR}$, where entry occurs is $W_{2,CI}^{H,NR} = \frac{2(2-2d)(1-c_{inc}^H)^2}{9} - F$.

. Hence, overall social welfare is $W_{CI}^{H,NR} = W_{1,CI}^{H,NR} + \delta W_{2,CI}^{H,NR} = \frac{(1-c_{inc}^{H})^2[9(B+1)+16\delta B]}{72} - \delta F$. Therefore, the welfare benefit from regulating a high-cost incumbent is

$$WB_{CI}^{H} \equiv W_{CI}^{H,R} - W_{CI}^{H,NR} = \frac{\left[9(1-2d)^2 + 4(1-4d)^2\delta\right](1-c_{inc}^{H})^2}{72(1+2d)}$$

which is increasing in d, since

$$\frac{\partial WB_{CI}^{H}}{\partial d} = \frac{[4d(1+d)(9+16\delta) - 27 - 20\delta](1-c_{inc}^{H})^2}{36(1+2d)^2}$$

is positive, given that $4d(1+d)(9+16\delta) - 27 - 20\delta > 0$ for all $d > 1/2$ and $\delta \in [0,1]$. ■

6.4 *Proof of Lemma 2*

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 strategy profile where only the incumbent (or only the regulator) chooses a type-dependent strategy cannot be supported as a PBE; as shown in Proposition 1 in Espinola-Arredondo et. al. (2011). We then show that a strategy profile where both informed agents select a type-dependent strategy can be sustained as a PBE.

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 its costs are high and $q^{L,sep}(t_1)$ when its 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 $M_{inc}^H(q^H(t_1^H), t_1^H) + \delta D_{inc}^H \geq M_{inc}^H(q^{L,sep}(t_1^H), t_1^H) + \delta D_{inc}^H$ 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, its 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 it 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 emission fee 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 $q^{L,sep}(t_1) > q^L(t_1)$. This is achieved by inducing the socially optimal output $q_{SO}^L = \frac{1-c_{inc}^L}{1+2d}$ by setting an emission fee t_1^A that solves $\frac{1-c_{inc}^L}{1+2d} = q^{L,sep}(t_1)$.

As shown in Espinola-Arredondo et. al. (2011), the only equilibrium that survives the Cho and Kreps' (1987) Intuitive Criterion is that where the low-cost incumbent selects output function $q(t_1) = q^A(t_1)$, where $q^A(t_1)$ solves C1, and the regulator sets a fee t_1^A that solves $q^A(t_1) = q_{SO}^L$ if priors satisfy $p \geq \frac{F-D_{ent}^L}{D_{ent}^H - D_{ent}^L} \equiv \overline{p}$, where $\overline{p} > 0$ for all $F > D_{ent}^L$ and $\overline{p} < 1$ for all $F < D_{ent}^H$. Hence, at the equilibrium output function $q^A(t_1)$, the emission fee t_1^A that solves $\frac{1-c_{inc}^L}{1+2d} = q^A(t_1)$ is $t_1^A = \frac{(1-c_{inc}^H)[A+\sqrt{3\delta}]-2(1-c_{inc}^L)}{A}$. Similarly, the incentive compatibility condition for the low-cost incumbent, C2, holds (when evaluated at the equilibrium fee t_1^A and output $q^A(t_1^A)$) if costs satisfy $c_{inc}^H < \frac{\sqrt{3\delta}+Ac_{inc}^L}{\sqrt{3\delta}+A} \equiv \widehat{\rho}$. ■

6.5 *Proof of Proposition 2*

Low-cost incumbent. In order to identify the welfare benefits from regulation, $WB^L_{HighPriors} \equiv W^{L,R}_{HighPriors} - W^{L,NR}_{HighPriors}$, let us separately find the welfare arising in the informative equilibrium when the regulator is present, $W^{L,R}_{HighPriors}$, and when he is absent, $W^{L,NR}_{HighPriors}$. When the regulator is present equilibrium welfare is $W^{L,R}_{HighPriors} = \frac{(1+\delta)(1-c^L_{inc})^2}{2A}$, whereas in the case that he is absent, for compactness, we provide the expression of $W^{L,NR}_{HighPriors}$ for parameter values $\delta = 1$, $c^H_{inc} = 1/2$ and $c^L_{inc} = 1/4$

$$W^{L,NR}_{HighPriors} = \frac{35 + 16A\sqrt{3} + 2d\left[69 + 2d\left(21 - 26d\right) - 8A\sqrt{3}\right]}{128A^2}.$$

Therefore, the welfare difference $WB^L_{HighPriors} \equiv W^{L,R}_{HighPriors} - W^{L,NR}_{HighPriors}$ becomes

$$WB^L_{HighPriors} = \frac{37 - 16A\sqrt{3} + 2d\left[3 + 8A\sqrt{3} + 2d\left(26d - 21\right)\right]}{128A^2}. \tag{A.4}$$

Note that if $\delta = 1$ and $c^L_{inc} = 1/4$ are fixed, while c^H_{inc} decreases to $c^H_{inc} = 1/3$, the welfare difference $WB^L_{HighPriors}$ becomes

$$\frac{373 - 160A\sqrt{3} + 2d\left[51 + 128A\sqrt{3} + 2d\left(290d - 177\right)\right]}{1152A^2}.$$

which is larger than A.4 (where $c^H_{inc} = 1/2$). Similarly, fixing parameters $c^H_{inc} = 1/2$ and $c^L_{inc} = 1/4$, but modifying δ from $\delta = 1$ to $\delta = 2/3$, we obtain welfare benefits of

$$\frac{15 - 8A\sqrt{2} + 2d\left[1 + 4A\sqrt{2} + 2d\left(10d - 9\right)\right]}{64A^2}.$$

which is lower than A.4 (where $\delta = 1$).

High-cost incumbent. In this case, both regulator and incumbent select the same actions under complete and incomplete information, thus yielding $W^{H,R}_{HighPriors} = W^{H,R}_{CI} = \frac{(1+\delta)(1-c^H_{inc})^2}{2+4d} - \delta F$ and $W^{H,NR}_{HighPriors} = W^{H,NR}_{CI} = \frac{(1-c^H_{inc})^2[9(B+1)+16\delta B]}{72} - \delta F$. Therefore, the welfare benefits from regulation satisfy $WB^H_{HighPriors} = WB^H_{CI} = \frac{\left[9(1-2d)^2+4(1-4d)^2\delta\right](1-c^H_{inc})^2}{72(1+2d)}$. ■

6.6 *Proof of Lemma 3*

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., $\mu(c_{inc}^H|q'(t_1'), t_1') = 1$. The same is true when both informed agents deviate, i.e., $\mu(c_{inc}^H|q'(t_1''), t_1'') = 1$.

Therefore, after observing an equilibrium emission fee t_1' and an equilibrium output level $q(t_1')$, the entrant enters if its expected profit from entering satisfies $p \times D_{ent}^H + (1-p) \times D_{ent}^L - F > 0$ or $p > \frac{F - D_{ent}^L}{D_{ent}^H - D_{ent}^L} \equiv \overline{p}$, where $\overline{p} \in (0,1)$ by definition. 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 $M_{inc}^H(q(t_1'), t_1') + \delta \overline{M}_{inc}^H$. If, instead, the incumbent deviates towards an off-the-equilibrium output $q'(t_1') \neq q(t_1')$, entry ensues and its profits become $M_{inc}^H(q'(t_1'), t_1') + \delta D_{inc}^H$, which are maximized at $q'(t_1') = q^H(t_1')$. Hence, the high-cost incumbent selects $q(t_1')$ if $M_{inc}^H(q(t_1'), t_1') + \delta \overline{M}_{inc}^H \geq M_{inc}^H(q^H(t_1'), t_1') + \delta D_{inc}^H$, or alternatively

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

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

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

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

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

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

Let us next analyze this condition. In particular, fee $t_2^{H,NE}$ induces socially optimal output given no entry in the second-period game. Similarly, fee $t_2^{H,E}$ induces socially optimal output given entry in the second-period game. Hence, output level coincides in both settings but the entrant incurs a fixed entry cost (reducing social welfare) if fee t_1^H is selected in the first-period game. Regarding first-period welfare, we can observe that fee t_1^H induces socially optimal output, $q^H(t_1^H) = q_{SO}^H$, whereas t_1' induces $q^L(t_1') = q_{SO}^L$, where $q^L(t_1') > q^H(t_1^H)$ since $q_{SO}^L > q_{SO}^H$, thereby inducing an inefficient output level. Therefore, the fee t_1' entails a first-period welfare loss relative to the complete information fee t_1^H, but avoids incurring a discounted entry cost δF. Hence, when the first-period welfare loss exceeds the fixed entry cost, the regulator facing a high-cost incumbent is not willing to choose a type-dependent fee t_1', and an uninformative strategy profile cannot be supported as a PBE. Otherwise, the regulator is willing to choose t_1' and the uninformative strategy profile can be sustained as a PBE.

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 $M_{inc}^L(q'(t_1), t_1) + \delta \overline{M}_{inc}^L$, which exceeds its equilibrium profit $M_{inc}^L(q(t_1), t_1) + \delta \overline{M}_{inc}^L$ for any $q'(t_1) \in (q(t_1), q^L(t_1))$ due to the concavity of the profit function. On the other hand, the high-cost incumbent obtains $M_{inc}^H(q(t_1), t_1) + \delta \overline{M}_{inc}^H$ in equilibrium. If instead, it deviates towards $q'(t_1) \neq q(t_1)$, $M_{inc}^H(q'(t_1), t_1) + \delta \overline{M}_{inc}^H$ is the highest profit that it can obtain, which exceeds its equilibrium profit if $q'(t_1) \in (q(t_1), q^H(t_1))$. Hence, beliefs can be restricted to $\mu\left(c_{inc}^H | q'(t_1), t_1\right) = 0$ 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 its 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 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 $M_{inc}^L(q'(t_1), t_1) + \delta \overline{M}_{inc}^L$, which exceeds its equilibrium profit 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 $M_{inc}^H(q'(t_1), t_1) + \delta \overline{M}_{inc}^H$, which exceeds its equilibrium profit 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 is larger than its 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 Intuitive Criterion. By instead deviating towards $q^L(t_1)$, the low-cost incumbent obtains $M_{inc}^L(q^L(t_1), t_1) + \delta \overline{M}_{inc}^L$ which exceeds its equilibrium profits. Similarly, the high-cost incumbent obtains $M_{inc}^H(q^L(t_1), t_1) + \delta \overline{M}_{inc}^H$ by deviating towards $q^L(t_1)$, which also exceeds its 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., $\mu\left(c_{inc}^H | q^L(t_1), t_1\right) = p$ 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 Intuitive Criterion. On one hand, $M_{inc}^L(q'(t_1), t_1) + \delta\overline{M}_{inc}^L$ is the highest payoff the low-cost incumbent obtains by deviating towards $q'(t_1) \neq q^L(t_1)$, which lies below its equilibrium profits since $M_{inc}^L(q'(t_1), t_1) + \delta\overline{M}_{inc}^L$ 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, $M_{inc}^H(q'(t_1), t_1) + \delta\overline{M}_{inc}^H$ 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 $M_{inc}^H(q^L(t_1), t_1) + \delta\overline{M}_{inc}^H \geq M_{inc}^H(q'(t_1), t_1) + \delta\overline{M}_{inc}^H$, which only holds for deviations closer to its 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., $\mu\left(c_{inc}^H | q'(t_1), t_1\right) = 1$, and enters. In contrast, its updated beliefs are unaffected after observing any other deviation. The high-cost incumbent's profits from deviating towards $q'(t_1)$ are hence $M_{inc}^H(q'(t_1), t_1) + \delta D_{inc}^H$, which are lower than its 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 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 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 subsidy 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 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 a 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 $SW^{H,E}(t_1^H, t_2^{H,E}) < SW^{H,NE}(t_1^L, t_2^{H,E})$. 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.

For the functional forms in the paper, condition C4 for the high-cost incumbent (evaluated at the equilibrium fee t_1^L and output $q^L(t_1^L)$) holds for all $c_{inc}^H < \frac{\sqrt{3}\sqrt{\delta}+Ac_{inc}^L}{\sqrt{3}\sqrt{\delta}+A} \equiv \widehat{\rho}$. Similarly, condition C6a for the regulator (evaluated at the equilibrium fee t_1^L and output $q^L(t_1^L)$) holds for all entry costs $F > \frac{(c_{inc}^H - c_{inc}^L)^2}{2\delta A}$. This condition on entry costs is compatible with $D_{ent}^L < F < D_{ent}^H$ if $\frac{(c_{inc}^H - c_{inc}^L)^2}{2\delta A} < D_{ent}^H$, which is satisfied when $c_{inc}^H < \frac{\sqrt{2A}+2Ac_{inc}^L}{2A+\sqrt{2A}} \equiv \overline{\rho}$. In addition, $\widehat{\rho} > \overline{\rho}$ implying that the cutoff $c_{inc}^H < \overline{\rho}$ is more restrictive than $c_{inc}^H < \widehat{\rho}$ for all $\delta > 1/2$. ■

6.7 *Proof of Proposition 3*

High-cost incumbent. Let us first show that the welfare benefit $WB_{LowPriors}^H \equiv W_{LowPriors}^{H,R} - W_{LowPriors}^{H,NR}$ is strictly positive for all parameter values, where

$$W_{LowPriors}^{H,R} = \frac{1 + \delta + \delta(c_{inc}^H)^2 - 2c_{inc}^H(1 + \delta - c_{inc}^L) - \left(c_{inc}^L\right)^2}{2 + 4d}$$

given that entry is deterred. In addition,

$$W_{LowPriors}^{H,NR} = \frac{(1 - c_{inc}^L)\left(3 - 2d - 4c_{inc}^H + Ac_{inc}^L\right) - (1 - c_{inc}^H)^2(2d - 3)\delta}{8}$$

where entry is also deterred. Therefore, the welfare benefit $WB_{LowPriors}^H \equiv W_{LowPriors}^{H,R} - W_{LowPriors}^{H,NR}$ is

$$WB_{LowPriors}^H = \frac{1}{8A}\left[D\left[D(1+\delta) + D\delta(c_{inc}^H)^2 + 2c_{inc}^H(2(1 - c_{inc}^L) - D\delta) + c_{inc}^L((3+2d)c_{inc}^L - 2A)\right]\right]$$

where $D \equiv -1 + 2d$. The welfare benefit $WB_{LowPriors}^H$ is strictly positive for our set of parameter values, where $d \in \left(\frac{1}{2}, 1\right)$, $c_{inc}^H < \frac{\sqrt{2A}+2Ac_{inc}^L}{2A+\sqrt{2A}} \equiv \overline{\rho}$ and $\delta \geq 1/2$.

Low-cost incumbent. The welfare benefit $WB_{LowPriors}^L \equiv W_{LowPriors}^{L,R} - W_{LowPriors}^{L,NR}$, coincides with that under complete information, WB_{CI}^L, since both regulator and incumbent select the same actions in both information contexts. Therefore, $W_{LowPriors}^{L,R} = W_{CI}^{L,R}$ and $W_{LowPriors}^{L,NR} = W_{CI}^{L,NR}$, entailing that $WB^L_{LowPriors} = WB^L_{CI}$. ■

6.8 *Proof of Proposition 4*

High priors. Let us first examine the case in which priors are high, $p > \overline{p}$. The difference between the welfare benefit from introducing environmental regulation under incomplete information, $WB^L_{HighPriors} \equiv W^{L,R}_{HighPriors} - W^{L,NR}_{HighPriors}$, and that under complete information, $WB^L_{CI} \equiv W^{L,R}_{CI} - W^{L,NR}_{CI}$, is

$$WB^L_{HighPriors} - WB^L_{CI} = \frac{19 - 16A\sqrt{3} + 2d\left[21 + 8A\sqrt{3} - 2d(3 + 10d)\right]}{128A^2}$$

which, for compactness, we consider parameter values $\delta = 1$, $c^H_{inc} = 1/2$ and $c^L_{inc} = 1/4$. This expression $WB^L_{HighPriors} - WB^L_{CI}$ is strictly positive for all $d \in \left(\frac{1}{2}, 1\right)$, and remains positive for all admissible parameter values, where $d \in \left(\frac{1}{2}, 1\right)$, $c^H_{inc} < \frac{\sqrt{3\delta} + Ac^L_{inc}}{\sqrt{3\delta} + A}$ and $\delta \in [0, 1]$.

When the incumbent's costs are high, both regulator and incumbent select the same actions under complete and incomplete information, thus yielding $W^{H,R}_{HighPriors} = W^{H,R}_{CI}$ and $W^{H,NR}_{HighPriors} = W^{H,NR}_{CI}$. Therefore, $WB^H_{HighPriors} = WB^H_{CI}$.

Low priors. First, when the regulator is absent, social welfare satisfies $W^{H,NR}_{LowPriors} < W^{H,NR}_{CI}$ if

$$c^H_{inc} > \frac{7 - 16d + 9c^L_{inc} + 3H}{8B} \equiv \rho_0$$

holds, where $H \equiv \left((1 - 4d)^2(1 + (c^L_{inc} - 2)c^L_{inc}) + 32BF\right)^{1/2}$ and $\delta = 1$. Otherwise, $W^{H,NR}_{LowPriors} > W^{H,NR}_{CI}$. The difference between the welfare benefit from introducing environmental regulation under incomplete information, $WB^H_{LowPriors} \equiv W^{H,R}_{LowPriors} - W^{H,NR}_{LowPriors}$, and that under complete information, $WB^H_{CI} \equiv W^{H,R}_{CI} - W^{H,NR}_{CI}$, is

$$WB^H_{LowPriors} - WB^H_{CI} = \frac{\left[5 - R + 4c^H_{inc}G + 9Dc^L_{inc}((3 + 2d)c^L_{inc} - 2A)\right]}{72A}$$

where $G \equiv -7 + 2d + 32d^2 + (9 - 18d)c^L_{inc}$, $R \equiv 4d(1 + 7d) + 4(1 - 4d)^2(c^H_{inc})^2$ and $\delta = 1$. The difference $WB^H_{LowPriors} - WB^H_{CI}$ is positive if and only if

$$c^H_{inc} > \frac{G + 3(1 - c^L_{inc})\sqrt{2}\sqrt{DA(-3 + 4dA)}}{2(1 - 4d)^2} \equiv \widetilde{\rho}.$$

However, $\widetilde{\rho} > \overline{\rho}$ and hence, for the parameter values that sustain the uninformative equilibrium ($c^H_{inc} < \overline{\rho}$), the difference $WB^H_{LowPriors} - WB^H_{CI}$ is negative. When the incumbent's costs are low, both regulator and incumbent select the same actions under complete and incomplete information, thus yielding $W^{L,R}_{LowPriors} = W^{L,R}_{CI}$ and $W^{L,NR}_{LowPriors} = W^{L,NR}_{CI}$. Therefore, $WB^L_{LowPriors} = WB^L_{CI}$. ■

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