School of Economic Sciences

Working Paper Series
WP 2016-13

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August, 2016

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August 4, 2016

Abstract

This paper analyzes an entry-deterrence model in which the incumbent decides whether to invest in research and development (R&D) that promotes clean technology. We consider the case in which the entrant could benefit from a technology spillover. We show that if the costs of R&D and the initial spillover are low, an increase in the spillover or probability of successful R&D increases the investment in R&D. In addition, higher levels of the spillover or probability of successful R&D make entry more attractive compared to a standard entry game. The results also suggest that if the spillover is low and/or pollution inflicts minor damage on the environment, no entry is socially optimal. Finally, from a policy perspective, when there is entry and pollution is present, the regulator should focus efforts on promoting technologies with a high probability of success instead of technologies with high spillover effects.

Keywords: Entry-deterrence; Emission fee; Research and development; Spillover.

JEL classification: H23; L12; O32; Q58.

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[*] We would like to especially thank Michael Delgado, Félix Muñoz-García, and Tristan Skolrud for their insightful comments and suggestions. We are also grateful to the participants at the Association of Environmental and Resource Economists session at the 91st annual Western Economic Association International conference.

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1. INTRODUCTION

A focus on cleaner technologies, such as sustainable developments, demand for renewable or sustainable energy, and climate change, are three major influences on the investment in research and development (R&D) within firms[1]. This behavior has been fueled as environmental regulation becomes more spread over countries and more demanding over time[2]. Therefore, firms' investment in R&D can be understood as a tool that firms use to ameliorate the cost imposed by environmental policy. The literature has shown that environmental regulation can potentially affect the market structure in which firms operate; see Dean and Brown (1995), Millimet et al. (2009), and Espínola-Arredondo and Muñoz-García (2013). However, the effect of regulation on firm's investment in R&D allowing for spillover effects has been overlooked.

The investment in R&D of clean technologies has consistently increased in the United States and the European Union. The Science and Engineering Indicators 2014 reports that between 2004 and 2012 clean energy investment in developed economies rose from \$19 billion to \$63 billion[3]. Our paper aims to answer the following questions: how does investment in R&D affect the entry decision in a polluting industry?, does the presence of spillover effects in R&D emphasize or ameliorate the entry patterns?, and, under which contexts is entry socially optimal? In answering these questions, we can better anticipate in which industries and which types of R&D lead to more social welfare improving outcomes. We develop an entry-deterrence model that considers an environmental policy and the investment in R&D with a spillover by the incumbent firm. The structure of the game is as follows: (1) in the first stage, the incumbent chooses a level of investment in the abatement technology; (2) in the second stage, the regulator sets an emissions tax based on the investment in

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[1] A survey developed by Battelle/R&D Magazine and presented in its *2014 R&D Magazine Global Funding Forecast* found that these are three of the top four factors influencing managers to invest in R&D: *http://www.rdmag.com/articles/2013/12/2014-r-d-magazine-global-funding-forecast*

[2] An overview of policies can be accessed at the Center for Climate and Energy Solutions' website: *http://www.c2es.org/international/key-country-policies/policies-key-countries*.

[3] This report can be found at the National Science Foundation's website: *http://www.nsf.gov/statistics/seind14/index.cfm/chapter-6*.

abatement technology by the incumbent and; (3) in the third stage, the entrant decides whether or not to enter, and if entry occurs, the firms compete *à la* Cournot, otherwise the incumbent acts as a monopolist. If the investment in R&D is successful, the incumbent employs this abatement technology in the third stage and the firms benefit from operating in a clean environment. The incumbent is not able to prevent any potential entrant from taking advantage of a portion of the benefits from the technology (spillover effect). The tax on emissions is paid in the third stage.

As mentioned before, one way firms seek to reduce the burden of an emissions tax is to invest in pollution reducing technology. Abatement R&D could include development of a production process that pollutes less, end-of-the-pipe abatement, or a number of other strategies. R&D is not always a successful endeavor, however, and is treated as a random process in our model. If R&D is successful, the incumbent firm patents a share of the innovation, but a proportion of the knowledge is not patentable, thus being available to potential entrants. For instance, potential entrants could benefit from operating in a cleaner environment through spending less effort on cleaning their own emissions.

The natural gas extraction industry represents the problem at hand. According to the US Bureau of Labor Statistics (BLS), this industry was concentrated in the 2000's, and it is regulated by the US Environmental Protection Agency (EPA)[4]. In addition, there has been considerable investment in environmental R&D within the industry, one example of this is Conoco Phillips[5]. A portion of the R&D focuses on cleaning and preventing groundwater from being contaminated with harmful substances. These technologies leave a cleaner environment and the benefits can spill over to a potential entrant. Hence, it is important to study how investment into environmental technologies with spillover is affected by the threat of entry.

Our paper explains how the investment decision, emissions tax rate, and quantity produced change due to the cost of the R&D, the spillover, and the severity of the environmental damage.

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[4] An overview of regulations can be found at *https://www.epa.gov/regulatory-information-sector/oil-and-gas-extraction-sector-naics-211*.

[5] Specifically, starting at page 19 of their 2015 Sustainability Report, found here: *http://www.conocophillips.com/sustainable-development/environment/water/managing-local-water-risks/Pages/default.aspx*.

This model builds on the entry-deterrence literature started in the 1970's (Spence (1977) and Selten (1978)) by considering environmental regulation and R&D. Dean and Brown (1995) show empirically that environmental policy can be a significant barrier to entry. The model presented in this paper assumes that even though there is environmental regulation, entry costs are sufficiently low to sustain the threat of entry. Espínola-Arredondo and Muñoz-García (2013) and Espínola-Arredondo et al. (2014) examine the effects of emission fees when there is a threat of entry under the cases of complete and incomplete information. However, they did not consider the effect of regulation on the investment of abatement technology with spillover.

A number of papers investigate the role of research and development structure (cooperative/non-cooperative) in an oligopolistic industry (D'Aspremont and Jacquemin (1988), Damania (1995), Miyagiwa and Ohno (2002), Poyago-Theotoky (2007), Stepanova and Tesoriere (2011), and Tesoriere (2015)), but are silent about its effect on entry deterrence. In addition, these papers focus on R&D with spillover effects that lower the production costs of the firms. In contrast, we consider R&D focused on lowering harmful emissions from production. Schoonbeek and de Vries (2009) develop an entry deterrence model showing that there are cases in which both the regulator and incumbent monopolist prefer a high enough emissions tax to deter entry but they do not consider investment in abatement technology. Our contribution to the literature is, hence, two-fold: (1) we analyze environmental R&D with spillover effects in the context of entry-deterrence, and (2) examine how environmental regulation promotes the investment in environmental R&D when entry threats are present.

Finally, Poyago-Theotoky (2007) primarily focuses on how the organization structure of R&D affects social welfare. Firms invest in environmental R&D simultaneously and the degree of cooperation between them vary. In contrast, our paper focuses on the relationships between the spillover, entry, and social welfare where only one firm invests in R&D. Specifically, our model analyzes how a monopolist's R&D decision responds to entry when there is a spillover of the benefits of abatement technology to a potential entrant. We also include probabilistic success in the R&D outcome as compared to the deterministic R&D considered in Poyago-Theotoky (2007).

Our results indicate that when there is entry, an increase in the probability of successful R&D and in the spillover produce an increase in social welfare. However, the effect of the former is higher than the latter as an increase in the spillover increases the total abatement in the market, whereas the benefit of an increase in the probability is concentrated within the firm investing in the technology. Under entry, it is more important for policy to focus on promoting the probability of successful R&D than on promoting investment into technologies with a spillover. One channel to achieve this objective is the creation of competitive grants where the most promising R&D projects, according to specialists, are subsidized[6]. Another channel that increases the probability of successful R&D is to increase funding to public research facilities whose discoveries are public goods. This policy has the side effect that the knowledge has a complete spillover if the results are sufficiently disseminated.

If the severity of damage from pollution is low, however, the incumbent's incentive to invest in R&D technology is low. As a consequence, entry of another firm into the market decreases an already low investment level, which results in social welfare from entry being lower than if there was no entry. In this case, the regulator has two options: to promote R&D activity or increase the barriers to entry through increasing the licensing costs for the entrant. The trade-off faced by the regulator is between decreasing expected emissions from more investment in R&D and increasing consumer surplus from entry. Finally, if entry does not ensue then an increase in the spillover has no effect on social welfare.

The next section of the paper presents the model and entry decision. Section 3 discusses the comparative static results, and compares equilibrium levels between entry and no entry. Section 4 concludes the paper.

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[6] One example is the Small Business Innovation Research (SBIR) program through the US Environmental Protection Agency. Through the EPA, SBIR funds feasible high-quality projects with a goal of producing a cleaner production process. More information can be found at: *https://www.epa.gov/sbir/about-sbir-program*.

2. Model

Consider a monopolist that faces an emissions tax and the threat of entry. In the first stage of the game, the polluting monopolist (incumbent) makes a decision on the amount to invest in R&D to develop abatement technology. The cost of investing in abatement is $\frac{1}{2}\gamma z^2$, where $\gamma > 0$ represents how costly it is to invest in R&D, and z is the total amount of abated pollution from production. Cost convexity indicates decreasing returns to investing in abatement. Considering the stochastic characteristic of the investment in R&D, we assume that $p \in [0, 1]$ represents the probability of successful R&D and, thus, $(1 - p)$ is the probability of unsuccessful R&D. Hence, the total expected abatement resulting from the investment in R&D becomes pz.

The overall amount of expected emissions produced by the incumbent is $E[\epsilon_i] = E[q_i - z] = q_i - pz$, where E is the expectation operator, ϵ denotes emissions, q_i is the output level, and the subscript i indicates the incumbent. As a result of the spillover, the entrant produces expected total emissions of $E[\epsilon_e] = q_e - \beta pz$, where the subscript e indicates the entrant. The technology spillover is β, where $\beta \in [0, 1]$. As previously discussed, the spillover in this context is understood as the entrant operating in a cleaner environment and, hence, not having to abate to receive these benefits (cleaner air, water, etc.), or the proportion of the incumbent's innovation that cannot be patented and thus can be freely used by the entrant.

The expected net environmental damage from the production of the good is

$$E\left[\tfrac{1}{2}d(q_i + q_e - (1 + \beta)z)^2\right],$$

where $d \in (1, \infty)$ measures the severity of the environmental damage from net emissions. This specification allows us to provide comparisons with Poyago-Theotoky (2007), who uses the same environmental damage function, and to guarantee an interior solution we assume that $d > 1$.

The entrant must incur a fixed cost to enter, $F > 0$. Firms face a linear demand $P(Q) = a - Q$, where P is price, $a > 0$, and $Q = q_i + q_e$ is the aggregate output level. Both firms have the same marginal cost of production c, where $a > c > 0$. Finally, the regulator sets an emission fee, t, that maximizes social welfare as defined by the sum of the producer and consumer surplus less the expected environmental damage.

Let us next describe the game structure in our model. In the first stage of the game, the incumbent firm makes a decision on the amount of abatement R&D (z) to invest in. In the second stage, the regulator maximizes social welfare by choosing the per unit emissions tax (t) levied on polluting firms. In the third and final stage, the outcome of the investment in R&D is realized (successful or unsuccessful), the entrant decides whether to enter the market, and production occurs (creating pollution in the process). If entry ensues, firms compete *à la* Cournot. If there is no entry, then the incumbent acts as a monopolist in the third stage. As a benchmark for comparison, we first solve the game for the case where there is no threat of entry, and afterwords we analyze the case of entry. In both cases the game is solved by backward induction.

2.1. **Case 1: No Entry**

We begin the analysis by examining the case where there is no threat of entry. Comparing these equilibrium results with those when entry threats are present will help identify how much investment in R&D is affected by entry. The structure and solving of the model begins with the third and final stage.

2.1.1. *Third Stage: Production*

First, let us briefly discuss the condition where there is no entry. Specifically, entry does not ensue when the entrant's profits are negative. We explore this condition further in section 2.2.4. If the entry is not profitable, the incumbent maximizes monopoly profits,

$$\max_{q_i} \Pi_i = (a - q_i)q_i - cq_i - t(q_i - pz),$$

which occurs at $q_i(t) = \dfrac{a-c-t}{2}$, yielding $\Pi_i(t) = \dfrac{(a-c-t)^2}{4}$. Hence, the incumbent has incentives to invest in R&D in order to reduce the emission fee.

2.1.2. *Second Stage: Regulation*

In the second stage, the regulator maximizes social welfare (SW) anticipating that only one firm operates in the market since there is no threat of entry (potential entrant's profits are negative). However, the regulator does not know if the R&D process is successful in this stage and makes its optimal choice of tax based on the expected abatement resulting from the investment in R&D. The regulator's problem is

$$\max_t SW = \int_0^{q_i(t)} (a-c-x)\,dx - E\left[\tfrac{1}{2}d\left[q_i(t)-z\right]^2\right] - \tfrac{1}{2}\gamma z^2,$$

where the first term is the sum of consumer and producer surplus from production, the second term is the expected environmental damage from emissions, and the third term is the incumbent's cost of investing in abatement technology. Differentiating with respect to t, and rearranging, gives the regulator's tax as a function of the level of R&D investment undertaken by the incumbent firm in the first stage,

$$t(z) = \frac{(d-1)(a-c)-2dpz}{d+1}. \tag{1}$$

The optimal tax rate is decreasing in both the probability of successful R&D and the level of investment in R&D. As the incumbent invests more in abatement, it is "rewarded" with a decrease in the tax rate. The incumbent uses this information to decide how much to invest in abatement R&D in the first stage.

2.1.3. *First Stage: Abatement*

In the first stage, the incumbent anticipates the actions in the second and third stages and solves

$$\max_z \Pi_i = (a-q_i(t(z)))q_i(t(z)) - cq_i(t(z)) - \tfrac{1}{2}\gamma z^2,$$

Differentiating with respect to z and rearranging, we can find, and present in the following proposition which summarizes the optimal investment in R&D, emission tax, and quantity produced in the absence of entry threats.

Proposition 1. *The equilibrium investment in abatement, tax, and quantity produced under no entry are (denoted by the 'ne' superscript):*

$$
\begin{aligned}
z^{ne} &= \frac{(a-c)(d-1)dp}{2d^2p^2+\gamma(d+1)^2}, && (2)\\
t^{ne} &= \frac{\gamma\left(d^2-1\right)(a-c)}{2d^2p^2+\gamma(d+1)^2}, && (3)\\
q^{ne} &= \frac{(a-c)\left(\gamma+d\left(\gamma+dp^2\right)\right)}{2d^2p^2+\gamma(d+1)^2}. && (4)
\end{aligned}
$$

If we consider the case in which there is no chance of successful R&D, $p = 0$, the equilibrium becomes

$$
\begin{aligned}
z^{ne}|_{p=0} &= 0,\\
t^{ne}|_{p=0} &= \frac{(d-1)(a-c)}{d+1},\\
q^{ne}|_{p=0} &= \frac{a-c}{d+1}.
\end{aligned}
$$

Intuitively, the incumbent does not invest in abatement R&D if the probability of success is nil. This case boils down to an equilibrium in which there is no R&D decision. That is, the regulator chooses an emissions tax that is positive and incentivizes the monopolist to internalize the externality from pollution.

2.2. Case 2: Entry

Similar to the case of no entry, we solve the game starting in the third stage with the production decision.

2.2.1. *Third Stage: Cournot Competition*

If entry occurs, both firms choose output simultaneously to maximize their profits. The incumbent's and the entrant's maximization problems are, respectively,

$$\max_{q_i} \Pi_i = (a - q_i - q_e)q_i - cq_i - t(q_i - pz), \text{ and}$$

$$\max_{q_e} \Pi_e = (a - q_e - q_i)q_e - cq_e - t(q_e - \beta pz) - F.$$

Taking first-order conditions and solving for the the output level, we obtain the symmetric solution of a standard Cournot model, $q_i = q_e = q = \frac{a-c-t}{3}$. Like the case of no entry, an increase in the emissions tax, t, decreases the profit-maximizing quantity. The entrant will join that market if there are positive profits from entering (discussed in depth in section 2.2.4).

2.2.2. *Second Stage: Regulation*

In the case of entry, the regulator seeks to maximize expected social welfare by choosing the emissions tax rate t anticipating entry into the market since potential entrant profits are positive,

$$\max_t SW = \int_0^{Q(t)} (a - c - x)\, dx - E\left[\frac{1}{2}d\left[Q(t) - (1+\beta)z\right]^2\right] - \left[\frac{1}{2}\gamma z^2 + F\right].$$

Differentiating and solving for t yields the optimal tax as a function of the investment in R&D, $t(z) = \frac{(a-c)(2d-1) - 3d(1+\beta)pz}{2(1+d)}$. The optimal tax rate is decreasing in the investment in abatement chosen by the incumbent, the spillover parameter β, and the probability of successful R&D, p. Specifically, when the spillover or abatement investment increases, the expected net emissions are lower, which lowers the expected environmental damage, thus lowering the emission fee. The incumbent firm uses this information in the first stage to decide the amount of abatement to invest in.

2.2.3. *First Stage: Abatement*

In the first stage, the incumbent chooses the investment in R&D that solves,

$$\max_z \Pi_i = (a - 2q)q - cq - \frac{1}{2}\gamma z^2,$$

where, from the second and third stage, we know $q(t)$ and $t(z)$, therefore $q(t(z))$. After taking a derivative with respect to and solving for z, we can present the next proposition which summarizes the equilibrium results under entry.

Proposition 2. *The equilibrium investment in abatement, tax, and quantity produced under entry are (denoted by the 'ent' superscript):*

$$z^{ent} = \frac{(\beta+1)d(d-1)(a-c)p}{2d^2p^2(\beta+1)^2 + 2\gamma(d+1)^2}, \tag{5}$$

$$t^{ent} = \frac{(a-c)\left(2\gamma\left(2d^2+d-1\right) + (\beta+1)^2d^2p^2\right)}{4(\beta+1)^2d^2p^2 + 4\gamma(d+1)^2}, \tag{6}$$

$$q^{ent} = \frac{(a-c)\left((\beta+1)^2d^2p^2 + 2\gamma(d+1)\right)}{4(\beta+1)^2d^2p^2 + 4\gamma(d+1)^2}, \tag{7}$$

given $d > 1$, z^{ent}, t^{ent}, and q^{ent} are positive.

2.2.4. *Entry condition*

We next investigate the entrant's decision to join the market based on the probability of successful R&D and the spillover. The entrant stays out of the market when its profit from entering the market is negative, that is, if the fixed cost to enter F is above $\bar{F}$,

$$\bar{F} \equiv (a - 2q^{ent})q^{ent} - cq^{ent} - t^{ent}(q^{ent} - \beta p z^{ent}).$$

Since $\bar{F}$ increases in the probability of successful R&D, p, and the spillover, β, entry becomes more attractive given that the entry cost that supports entry becomes less demanding. In particular, as either of these parameters increase, the expected benefit to the entrant increases and the fixed cost to enter becomes less imposing to the entry decision[7]. Figure 1 shows this relationship between the entrant's profits and the fixed cost to enter[8]. When the fixed cost is large enough, the entrant's

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[7] These comparative statics and the value of $\bar{F}$ are presented in the appendix, section 4.1.

[8] Parameter values for all figures (unless specified otherwise) are: $a = 10$, $c = 1$, $p = 0.5$, $d = 2.5$, $\beta = 0.75$, and $\gamma = 3$.

profit becomes negative and there is no threat of entry. This is represented by all the values of F greater than 1.9 when $\beta = 0.75$. As p or β increases, the profit line shifts upward and the entrant experiences positive profits for a larger set of F. In this context, there is more expected abatement of pollution or a larger spillover, both of which decrease the marginal cost of production for the entrant (see the rightward shift in Figure 1 for an increase in β from 0.75 to 0.9).

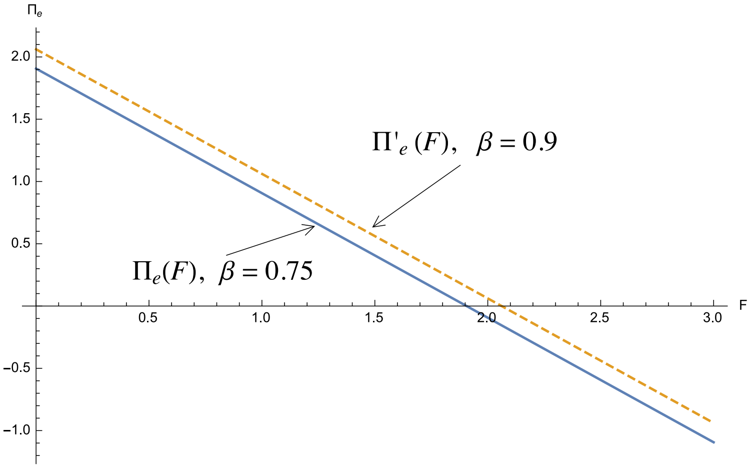


Figure 1. The entrant's potential profits as a function of the fixed cost F.

Next, we analyze the entry decision based on the the level of investment in R&D by the incumbent. This allows us to determine if the investment increases the attractiveness of entry. For this comparative static, we consider the entrant's profits as follows,

$$\Pi_e(z) = (a - 2q(t(z)))q(t(z)) - cq(t(z)) - t(z)(q(t(z)) - \beta pz) - F.$$

We cannot determine the sign of the comparative static of the incumbent's investment in R&D on the entrant's profits for all values of z. We can, however, determine the sign of the comparative static evaluated at $z = 0$. By explicitly substituting equilibrium values for t and q into the entrant's profit function and taking the derivative with respect to z, we obtain

$$\left.\frac{\partial \Pi_e}{\partial z}\right|_{z=0} = \frac{p(a-c)\left(2\beta d^2 + 2\beta d + d - \beta\right)}{2(d+1)^2} > 0,$$

which is unambiguously positive. As a consequence, the entrant's profits increase if the incumbent decides to invest in the first unit of abatement technology and, therefore, investment in R&D can make entry more attractive if the threat of entry exists (i.e. if $\Pi_e|_{z=0} > 0$). This suggests that if the regulator supports (through environmental regulation) the initial investment in R&D that has spillover characteristics, then he will indirectly increase competition in the market.

2.3. Comparative Statics

We now investigate how the equilibrium levels of quantity (q), tax (t), and investment in R&D (z) are affected by a change in the spillover (β, which is only relevant in the case of entry), severity of the environmental damage (d), investment cost (γ), and the probability of successful R&D (p) in the case of entry. The next corollary summarizes our findings which hold for the case of entry and no entry.

Corollary 1. *Regardless of the entrant's decision, an increase in the environmental damage increases the investment in R&D and the emissions fee, but decreases the output level. In addition, an increase in the cost of investment decreases the investment in R&D and output, but increases the emissions fee.*

As the environmental damage increases, the investment and tax rate increase, and the quantity produced decreases. These three results go hand-in-hand. Since the severity of damage is high, there is a greater marginal damage to society for each unit of production and the incumbent expects a high emissions tax. Hence, the incumbent firm increases its investment in abatement, which lowers the expected emissions per unit in production. Even though there is an increase in R&D, the environmental damage from production increases, which increases the emission fee. In addition, the increase in tax rate produces a higher marginal cost, so firms scale back their production.

When the cost of investment in R&D (γ) increases, the incumbent firm faces a higher marginal cost of abatement. Therefore, the incumbent reacts by investing in a lower amount of abatement, which entails an increase in emissions, ultimately causing more environmental damage. In response to the increase in emissions, the social planner increases the tax rate, thus, increasing the marginal cost for each unit produced and, therefore, decreasing the firms' production. Corollary 2 summarizes the findings of a change in the probability of successful R&D under no entry.

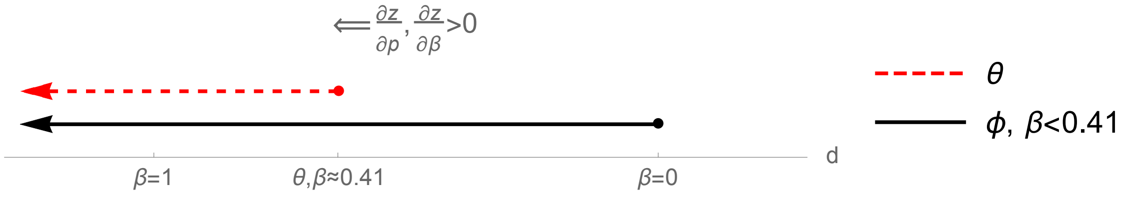
Corollary 2. *Under no entry, an increase in the probability of successful R&D decreases (increases) the emission fee (output level, respectively). In addition, the investment in R&D increases in the probability of successful R&D if* $d < \theta$*, where* $\theta \equiv \frac{\sqrt{\gamma}}{p\sqrt{2} - \sqrt{\gamma}}$*, and* $\gamma < 2p^2$*. However, the investment decreases in the probability of successful R&D if* $\gamma > 2p^2$*.*

The investment in R&D increases in the probability of success when there is no entry if the cost of investment is sufficiently low and the environmental damage is lower than θ. That is, the probability of successful R&D by itself does not promote investment in R&D in the absence of entry. If the cost of investment is low, it requires a sufficiently low environmental damage in order to encourage investment. In addition, a high level of environmental damage does not necessarily induce an increase in R&D if p increases, it also needs to be accompanied by inexpensive R&D. However, if the cost of investment is sufficiently high, an increase in the probability of successful R&D decreases investment. We next discuss the comparative static results for the case of entry.

Corollary 3. *Under entry, an increase in the probability of successful R&D or the spillover decreases the emission fee and increases the output level. In addition, the investment in R&D increases in the probability of successful R&D (or an increase in the spillover) if* $d < \phi$*, where* $\phi \equiv \frac{\sqrt{\gamma}}{p(\beta+1) - \sqrt{\gamma}}$*, and* $\gamma < (1+\beta)^2 p^2$*. However, an increase in the probability of successful R&D or the spillover decreases investment if* $\gamma > (1+\beta)^2 p^2$*.*

From corollary 3, we can infer that if the environmental damage and cost of R&D are low, i.e. $d < \phi$ and $\gamma < (1+\beta)^2 p^2$, then an increase in the spillover increases investment in R&D. However, higher values of β reduce the cutoff ϕ making the condition on the environmental damage that supports an increase in R&D, due to an increase in the probability of success, more demanding.

If we compare the cutoff for environmental damage that supports an increase in R&D under no entry, θ, with that under entry, ϕ, we obtain that in the case of $\beta > \sqrt{2}-1 \approx 0.41$, the cutoff θ exceeds ϕ. This result indicates that the investment in R&D is more likely to increase with the probability of success under no entry than entry. In the case of no entry, the free-riding benefits from R&D are absent, leading the incumbent to invest more. In addition, as the spillover increases, the incumbent's benefit from investment decreases as the entrant benefits more from the abatement technology and the incentive to invest diminishes. Figure 2(a) shows the regions of environmental damage where an increase in the probability of success (or spillover if there is entry) increases the investment in R&D when $\beta < 0.41$, and figure 2(b) shows this region when $\beta > 0.41$.



(a) Low spillover

(b) High spillover

FIGURE 2. Region where the comparative statics $\frac{\partial z}{\partial p}$ and $\frac{\partial z}{\partial \beta}$ are positive given values of the spillover β over a range of environmental damage d.

2.4. Equilibrium Comparison

Next, we compare the no entry (equations (2), (3), (4)) with the entry equilibrium (equations (5), (6), and (7)). We start with the investment in R&D.

Corollary 4. *The incumbent invests more in R&D when there is no threat of entry into the market.*

When there is entry, even without a spillover (i.e. $\beta = 0$), any investment in abatement lowers the emission fee faced by both firms (observed in section 2.2.2).With a lower tax, the entrant can benefit from a lower effective marginal cost and, thus, produce more, which ultimately lowers the incumbent's profits. This leads to the incumbent reducing its investment in R&D when there is threat of entry.

Corollary 5. *The incumbent produces more when there is no threat of entry. In addition, the aggregate quantity under no entry is greater (lower) than that under entry if* $\beta < 0.41$ *(if* $\beta > 0.41$*, respectively).*

When there is entry, the incumbent decreases its production and investment (from Lemma 1) in R&D compared to the case of no entry. The amount in which the incumbent decreases production is dependent on the spillover. From Corollary 2, we know the tax is decreasing in the spillover and that the quantity produced is increasing in the spillover. In addition, we find that when the spillover is low enough, the incumbent's output reduces to less than half of what it would be if there was no entry.

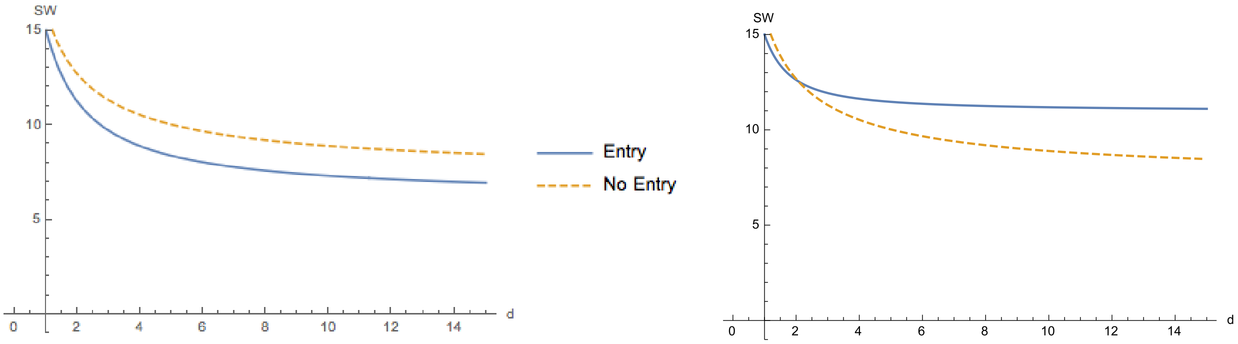
The comparison of the tax rate is not as straight forward. When the spillover is high, it can be that the tax rate is lower when there is entry than if there was no entry. With a spillover of $\beta < 1$, the total amount of abatement per unit of output is lower in the case of entry than if there is no entry. Since the entrant's emissions are not abated at the same level as the incumbent, there are more emissions per unit produced in the industry as a whole. Therefore, more expected environmental damage per unit in the case of entry applies upward pressure on the tax rate. When the spillover is high, the difference in abatement per unit produced between entry and no entry is small, so the tax rate is less than if the spillover is small. In both cases, a high environmental damage coupled with an increase in the probability of successful R&D decreases the investment in R&D, which decreases the tax rate. If the spillover is low ($\beta < \sqrt{2} - 1 \approx 0.41$) and the probability of successful R&D increases, there is a level of environmental damage that would cause the investment in R&D to increase if there is entry and decrease R&D if there is not entry . The combination of these points facilitate a situation where the emissions tax is lower under entry than no entry.

2.5. Social Welfare Comparison

Most critical to policy makers is the comparison between the social welfare under entry and no entry. Intuitively, we expect to identify cases where entry into the market is socially optimal and also cases where entry lowers social welfare. The complexity of the equilibrium social welfare functions does not make comparisons intuitive or tractable. Therefore, we analyze the social welfare numerically and graphically (Figure 3) with parameter values consistent with the rest of the analysis.

Lemma 1. *If the spillover is low and either the environmental damage is low or fixed cost of entry is high, then* $SW^{ne} > SW^{ent}$*. However, if the spillover or environmental damage are high and the fixed cost to enter is low, then* $SW^{ent} > SW^{ne}$*.*

The first result of lemma 1 is a special case in the setting in which there is no technology spillover ($\beta = 0$). In this context, social welfare under no entry is unambiguously higher than that under entry regardless of the parameter values. When there is entry and no spillover, the environmental damage increases since the entrant's pollution is not abated and total production increases. The increase in environmental damage outweighs the benefits to the consumers from increased competition. When the spillover is present, the environmental damage, d, cost of abatement γ, and the fixed cost of entry F play a role in deciding which case yields the greater benefit to society. No entry yields a higher social welfare when there is a high cost to enter the market or if there is a low spillover. Since the fixed cost enters linearly into the social welfare function when there is entry, a higher F shifts the social welfare downward. Figure 3(a) and 3(b) show the comparison of the social welfare functions when there is entry and when there is no entry for different values of the spillover. Our result suggests that the regulator should support investment in R&D that produces a spillover since this investment would promote competition and generate a higher level of social welfare.



(a) Low spillover, $\beta = 0.15$

(b) High spillover, $\beta = 0.75$

FIGURE 3. Comparison of social welfare when there is entry and when there is no entry. $F = 1$.

For a low value of the spillover, social welfare under no entry is always higher than the case of entry, see figure 3(a). When the spillover increases, social welfare under entry increases as there is an increase in the positive externality from abatement R&D without any added cost. This creates a crossing point for the social welfare functions in the figure 3(b) with respect to the severity of damage. For low levels of damage, it is socially optimal for only one firm to operate in the market. For high levels of damage, however, the opposite argument applies.

The severity of damage needed for entry to be socially optimal, or "critical damage level," decreases as the spillover increases. For example, if $\beta = 0.75$, like in figure 3(b), the critical damage level is about 2.07. When $\beta = 0.9$, the critical damage level is 1.75. This means that, at higher levels of β, entry is socially optimal for lower levels of d. When β is less than 0.3, however, social welfare under no entry is unambiguously higher than entry for all environmental damages.

Finally, the critical damage level increases as the cost of investing in abatement technology γ increases. When technology is more costly, entry is socially optimal at a higher level of the environmental damage. Since the spillover decreases the marginal benefit of investment in R&D for the incumbent, the incumbent decreases its investment when there is entry into the market.

When the investment is costly, the incumbent abates at a low level. Combining this with the case of entry, the incumbent abates at an even lower level.

Comparison with Poyago-Theotoky (2007). We next compare the equilibrium results from our model to that developed by Poyago-Theotoky (2007, hereafter P-T)[9]. Our model facilitates this comparison if we set $p = 1$, so that there is no uncertainty in the result of the R&D. Since P-T assumes that two firms are already operating in the market and both are investing in abatement technology, there will be different incentives for the firms to invest in R&D. Specifically, we compare the equilibrium abatement, tax, and quantity produced under entry from our model to the case in which firms choose the investment in R&D non-cooperatively in P-T.

First, we explore the comparison between individual firm investment in R&D in P-T (referred to as the non-cooperative investment) to the incumbent's level of investment in our model. Using parameter values consistent to our previous analysis, we observe that the level of investment is higher in the non-cooperative case than in the case of entry in our paper for all values of the spillover. However, an increase of the environmental damage or lower cost of R&D increases the investment in our model compared to P-T. The spillover in our model does not come with as much of a benefit as that in P-T's model. Since the entrant cannot invest in R&D, the incumbent does not realize any benefits from the entrant through the spillover. Hence, the reduction in the emissions tax through the investment in R&D is only reacting to the incumbent's decision to invest. Therefore, the changes in the environmental damage and cost to invest are going to affect the incumbent's abatement decision in our model more than a firm in P-T's model. If d is high enough (or γ low enough) it can be the case that the level of investment is higher in our entry framework than P-T at high levels of the spillover. Specifically, the higher the value of d is (or lower γ, respectively), the lower the spillover needed to obtain the case where the incumbent's investment (in our model) is higher than the non-cooperative case. These cases are illustrated in figure 4.

Since both firms are abating their pollution in the non-cooperative P-T model it is worthwhile to compare the total amount of abatement in each framework. We find that there is always more

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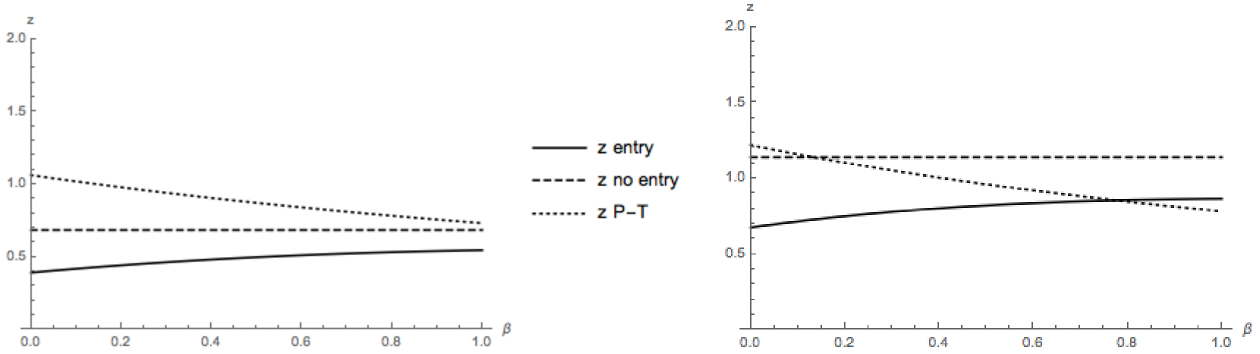
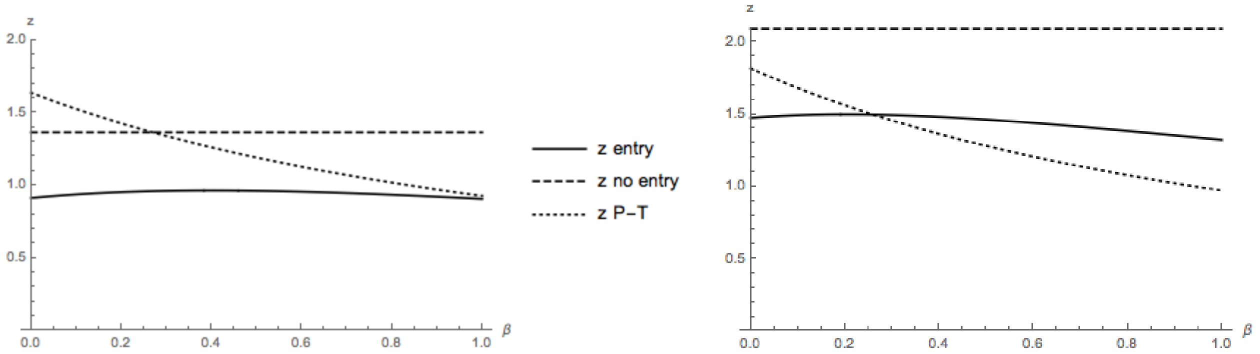
[9] Since we used the same environmental damage function, cost of investing in R&D, model structure, and notation the comparison is straightforward. The explicit comparison is provided in the appendix.

total abatement in the P-T's model than the case of entry in our model for all allowable parameter values. As discussed before, this is the direct result of both firms having the ability to invest in R&D in P-T's model.



(a) Parameters consistent with our analysis: $d = 2.5$, $\gamma = 3$

(b) High damage, $d = 5$ and $\gamma = 3$



(c) Low cost: $d = 2.5$, $\gamma = 1$

(d) High damage and low cost, $d = 5$ and $\gamma = 1$

FIGURE 4. Comparison investment in abatement between our framework and the P-T framework over the range of the spillover β.

Finally, we analyze if the entry-deterrence behavior in our model induces the incumbent to invest more in R&D than in the case of P-T. Focusing on the no entry case, the results indicate that the incumbent invests more in abatement in the entry deterrence case when the environmental damage is high and the cost of investment is low. Specifically, the conditions on the environmental damage and cost of investment that result in more abatement in the entry deterring case compared to P-T are less restrictive. This can be seen particularly in figures 4(a) and (d).

2.6. **Policy Considerations**

From the analysis, it has been shown that both a large spillover and a high probability of successful R&D are important in leading the industry to a more socially optimal outcome when there is entry. These are both parameters that are taken as exogenous by the firms, but can potentially be affected by policy not considered in the model itself. To increase the spillover, a regulator can promote R&D projects that inherently have a high spillover (any decrease in pollution that reduces costs for any nearby producer) or create (subsidize) sustainability training programs for workers in polluting industries. To increase the probability of successful R&D, the regulator can promote research in the public sector that would help with the private R&D process. This would promote the development of technologies that, from the beginning, have a better chance of being successful and feasible in implementation. In the absence of any budget constraints, a regulator would be advised to pursue both types of policy to maximize the spillover and probability of successful R&D in a polluting industry. If there is a budget constraint, however, then it may only be possible to implement one policy. To determine which policy is most efficient, we compare

$$\frac{\partial SW^{ent}}{\partial p} > \frac{\partial SW^{ent}}{\partial \beta}, \tag{8}$$

which holds for all parameter values since $\beta, p \in [0,1]$. If increasing the probability of successful R&D is feasible, then it is the recommended policy direction assuming that it has the same cost of implementation than a policy promoting the spillover. Since increasing the spillover also improves social welfare when there is entry, it is worth a careful examination of the costs of each policy compared to the expected benefits from increasing each parameter.

A second policy consideration arises in the situation where it is socially optimal that there is no entry into the market, even though the threat of entry exists (since potential entrant profits are positive). Since the emission fee is set to maximize social welfare depending on the number of firms in the market, it would not be optimal to use this as a tool to deter entry. Instead, the regulator could increase the fixed cost of entry F when entry is not socially optimal through an increase in licensing fees or other administrative costs. If the costs are raised sufficiently, so that there is no longer a threat of entry, the regulator has successfully facilitated a situation that maximizes social welfare.

3. CONCLUSION

We analyze how an entry-deterrence model is affected by the inclusion of investment in R&D with the possibility of spillover to a potential entrant. From a social welfare point of view, we show that when the spillover is low enough or a low environmental damage is accompanied by a high spillover, having only one firm in the market is socially desirable. A second firm entering into the market is more beneficial for society when the severity of the environmental damage is high, the spillover is high, and the probability of successful R&D is high. If entry is inevitable, then it is best for policy to focus on increasing the probability of successful R&D than to increase the spillover of the technology. If it is not possible to increase the probability of successful R&D, then society is still better off if the spillover is increased.

There is a trade-off when we consider entry into the market, since it benefits consumers, but it also increases the environmental damage from increased production. Whether or not entry is beneficial to society depends heavily on the spillover, the severity of the damage, and the fixed cost of entry. If the fixed cost to enter is sufficiently low enough, it is profitable for a second firm to enter the market even if it is not socially optimal. When the spillover is small, the regulator has three options to maximize welfare: (1) create a larger barrier to entry for a potential entrant by requiring large licensing fees; (2) allow entry and promote the spillover from any R&D undertaken by the incumbent; or (3) increase the probability of successful R&D, which would reduce the expected amount of emissions regardless of if entry does occur.

The next step is to further integrate the entry model with that of P-T, where there are multiple incumbents facing the threat of entry. The combination of these two frameworks would combine downward pressures on the already low investment in abatement technology in each framework. This combination could decrease the investment even closer to zero, or it could potentially yield a level of investment that lies between the two frameworks. Another extension to the model could incorporate entry of another firm that produces a good that is either a (imperfect) substitute or complement to the incumbent's good. In this situation, it may not be privately optimal for the incumbent to decrease its investment when there is entry since it is not directly negatively impacting the goods market competition like that of an identical good.

4. APPENDIX

4.1. **Entry Decision**

First, we examine the effect of a change in the probability of successful R&D, p, then a change in the spillover β on the fixed cost that blockades entry. In equilibrium, any fixed cost F above $\bar{F}$ will blockade entry where,

$$\bar{F} \equiv \frac{(a-c)^2\left(\beta^4 d^3(p+1)^3(3dp+d-2p)+4\gamma^2(d+1)^2+4\beta^2\gamma d(d+1)(p+1)(2(d-1)dp+d+p)\right)}{16\left(\beta^2 d^2(p+1)^2+\gamma(d+1)^2\right)^2}.$$

The comparative static of a change in successful R&D on $\bar{F}$ is

$$\frac{\partial \bar{F}}{\partial p} = \frac{A\left[\beta^4 d^4(p+1)^4+\beta^2\gamma d^2(d+1)(p+1)^2(7d-2(d-4)p-1)+2\gamma^2(d+1)^2(B)-2p-1)\right]}{8\left(\beta^2 d^2(p+1)^2+\gamma(d+1)^2\right)^3} > 0,$$

since $a > c > 0$, $p > 0$, $d > 1$, and $\gamma > 0$, where $A = \beta^2(d-1)d(a-c)^2$, $B = d(4(d+1)p + 2d + 3$

The comparative static of a change in spillover on $\bar{F}$ is

$$\frac{\partial \bar{F}}{\partial \beta} = \frac{\beta\gamma d\left(d^2-1\right)(p+1)(a-c)^2\left[2\gamma(d+1)((2d(d+1)-1)p+\beta^2 d^2(p+1)^2(4p+d(1-p))-d)\right]}{4\left(\beta^2 d^2(p+1)^2+\gamma(d+1)^2\right)^3} > 0,$$

since $a > c > 0$, $p > 0$, $d > 1$, and $\gamma > 0$.

4.2. **Comparative Statics**

4.2.1. *Proof of Corollary 1.*

Let us now examine the effect of a change in the environmental damage or abatement costs on the equilibrium results, first in the case of no entry and, second, when there is entry. The case of no entry:

$$\frac{\partial z^{ne}}{\partial d} = \frac{p(a-c)\left(2d^2p^2+\gamma(d+1)(3d-1)\right)}{\left(2d^2p^2+\gamma(d+1)^2\right)^2} > 0,$$

$$\frac{\partial z^{ne}}{\partial \gamma} = -\frac{(d-1)d(d+1)^2p(a-c)}{\left(2d^2p^2+\gamma(d+1)^2\right)^2} < 0,$$

$$\frac{\partial t^{ne}}{\partial d} = \frac{2\gamma(a-c)\left(\gamma(d+1)^2+2dp^2\right)}{\left(2d^2p^2+\gamma(d+1)^2\right)^2} > 0,$$

$$\frac{\partial t^{ne}}{\partial \gamma} = \frac{2d^2\left(d^2-1\right)p^2(a-c)}{\left(2d^2p^2+\gamma(d+1)^2\right)^2} > 0,$$

$$\frac{\partial q^{ne}}{\partial d} = -\frac{\gamma(a-c)\left(\gamma(d+1)^2+2dp^2\right)}{\left(2d^2p^2+\gamma(d+1)^2\right)^2} < 0,$$
$$\frac{\partial q^{ne}}{\partial \gamma} = -\frac{d^2\left(d^2-1\right)p^2(a-c)}{\left(2d^2p^2+\gamma(d+1)^2\right)^2} < 0,$$

since $a > c > 0$, $p > 0$, $d > 1$, and $\gamma > 0$. The case of entry:

$$\frac{\partial z^{ent}}{\partial d} = \frac{(\beta+1)p(a-c)\left((\beta+1)^2d^2p^2+\gamma(d+1)(3d-1)\right)}{2\left((\beta+1)^2d^2p^2+\gamma(d+1)^2\right)^2} > 0,$$
$$\frac{\partial z^{ent}}{\partial \gamma} = -\frac{2(\beta+1)(d-1)d(d+1)^2p(a-c)}{\left(2(\beta+1)^2d^2p^2+2\gamma(d+1)^2\right)^2} < 0,$$
$$\frac{\partial t^{ent}}{\partial d} = \frac{3\gamma(a-c)\left(\gamma(d+1)^2+(\beta+1)^2dp^2\right)}{2\left((\beta+1)^2d^2p^2+\gamma(d+1)^2\right)^2} > 0,$$
$$\frac{\partial t^{ent}}{\partial \gamma} = \frac{3(\beta+1)^2d^2\left(d^2-1\right)p^2(a-c)}{4\left((\beta+1)^2d^2p^2+\gamma(d+1)^2\right)^2} > 0,$$
$$\frac{\partial q^{ent}}{\partial d} = -\frac{\gamma(a-c)\left(\gamma(d+1)^2+(\beta+1)^2dp^2\right)}{2\left((\beta+1)^2d^2p^2+\gamma(d+1)^2\right)^2} < 0,$$
$$\frac{\partial q^{ent}}{\partial \gamma} = -\frac{(\beta+1)^2d^2\left(d^2-1\right)p^2(a-c)}{4\left((\beta+1)^2d^2p^2+\gamma(d+1)^2\right)^2} < 0,$$

since $a > c > 0$, $p > 0$, $d > 1$, and $\gamma > 0$.

4.2.2. *Proof of Corollary 2.*

We next examine the derivatives of z, t, and q with respect to p in the case of no entry:

$$\frac{\partial t^{ne}}{\partial p} = -\frac{4\gamma d^2\left(d^2-1\right)p(a-c)}{\left(2d^2p^2+\gamma(d+1)^2\right)^2} < 0,$$
$$\frac{\partial q^{ne}}{\partial p} = \frac{2\gamma d^2\left(d^2-1\right)p(a-c)}{\left(2d^2p^2+\gamma(d+1)^2\right)^2} > 0,$$
$$\frac{\partial z^{ne}}{\partial p} = \frac{(d-1)d(a-c)\left(\gamma(d+1)^2-2d^2p^2\right)}{\left(2d^2p^2+\gamma(d+1)^2\right)^2} \lesseqgtr 0.$$

The sign of $\gamma(d+1)^2-2d^2p^2$ determines the sign of $\frac{\partial z^{ne}}{\partial p}$. If $\left(\gamma(d+1)^2-2d^2p^2\right)$ is positive then $\frac{\partial z^{ne}}{\partial p} > 0$, which occurs if $d < \frac{\sqrt{\gamma}}{p\sqrt{2}-\sqrt{\gamma}} \equiv \theta$ and $\gamma < 2p^2$. If $\gamma > 2p^2$, then $\theta < 0$, and $\frac{\partial z^{ne}}{\partial p} < 0$ for all permissible values of d.

4.2.3. *Proof of Corollary 3.*

Let us now consider the case of entry:

$$\begin{aligned}
\frac{\partial t^{ent}}{\partial p} &= -\frac{3(\beta+1)^2\gamma d^2\left(d^2-1\right)p(a-c)}{2\left((\beta+1)^2d^2p^2+\gamma(d+1)^2\right)^2} < 0, \\
\frac{\partial q^{ent}}{\partial p} &= \frac{(\beta+1)^2\gamma d^2\left(d^2-1\right)p(a-c)}{2\left((\beta+1)^2d^2p^2+\gamma(d+1)^2\right)^2} > 0, \\
\frac{\partial z^{ent}}{\partial p} &= \frac{\overbrace{(\beta+1)(d-1)d(a-c)}^{(+)}\overbrace{\left(\gamma(d+1)^2-(\beta+1)^2d^2p^2\right)}^{(?)}}{\underbrace{2\left((\beta+1)^2d^2p^2+\gamma(d+1)^2\right)^2}_{(+)}} \lesseqgtr 0.
\end{aligned}$$

The sign of $\frac{\partial z^{ent}}{\partial p}$ is determined by the sign of $(\gamma(d+1)^2-(\beta+1)^2d^2p^2)$, since $d>1$ and $a>c$. If $d < \frac{\sqrt{\gamma}}{p(\beta+1)-\sqrt{\gamma}} \equiv \phi$ and $\gamma < p^2(1+\beta)^2$, then $\frac{\partial z^{ent}}{\partial p} > 0$. If $\gamma > p^2(1+\beta)^2$, then $\phi < 0$, therefore $\frac{\partial z^{ent}}{\partial p} > 0$.

We next evaluate how a change in the spillover will affect the equilibrium results when there is entry:

$$\begin{aligned}
\frac{\partial t^{ent}}{\partial \beta} &= -\frac{3(\beta+1)\gamma d^2\left(d^2-1\right)p^2(a-c)}{2\left((\beta+1)^2d^2p^2+\gamma(d+1)^2\right)^2} < 0, \\
\frac{\partial q^{ent}}{\partial \beta} &= \frac{(\beta+1)\gamma d^2\left(d^2-1\right)p^2(a-c)}{2\left((\beta+1)^2d^2p^2+\gamma(d+1)^2\right)^2} > 0, \\
\frac{\partial z^{ent}}{\partial \beta} &= \frac{\overbrace{(d-1)dp(a-c)}^{(+)}\overbrace{\left(\gamma(d+1)^2-(\beta+1)^2d^2p^2\right)}^{(?)}}{\underbrace{2\left((\beta+1)^2d^2p^2+\gamma(d+1)^2\right)^2}_{(+)}} \lesseqgtr 0.
\end{aligned}$$

The sign of $\frac{\partial z^{ent}}{\partial \beta}$ is determined by the sign of $(\gamma(d+1)^2-(\beta+1)^2d^2p^2)$, since $d>1$ and $a>c$. The conditions determining the sign of $\frac{\partial z^{ent}}{\partial p}$ are the same as those that determine the sign of $\frac{\partial z^{ent}}{\partial \beta}$.

4.3. **Equilibrium Comparison**

This section of the appendix corresponds to section 2.4 of the text and goes through the calculations showing the comparisons of the equilibrium levels of z, t, and q in the cases of entry and no entry.

Proof of Corollary 4.

First, we can show that $z^{ent} < z^{ne}$ for all parameter values:

$$z^{ent} < z^{ne},$$

$$\frac{(\beta+1)(d-1)(a-c)dp}{2d^2p^2(\beta+1)^2+2\gamma(d+1)^2} < \frac{(a-c)(d-1)dp}{2d^2p^2+(d+1)^2\gamma},$$

which simplifies to,

$$\frac{-2d^2p^2(1+\beta)\beta}{(d+1)^2(1-\beta)} < \gamma$$

since $d > 1$, $0 < p < 1$, $0 < \beta < 1$, and $\gamma > 0$, then $z^{ent} < z^{ne}$.

Proof of Corollary 5.

Let us next examine if the output level under no entry exceeds that under entry.

$$q^{ne} > q^{ent},$$

$$\frac{(a-c)(\gamma(1+d)+d^2p^2)}{2d^2p^2+\gamma(1+d)^2} > \frac{(a-c)\left((\beta+1)^2d^2p^2+2\gamma(1+d)\right)}{4(\beta+1)^2d^2p^2+4\gamma(1+d)^2},$$

which simplifies to,

$$\underbrace{4\gamma(1+d)d^2p^2\overbrace{\left((\beta+1)^2-1\right)}^{(+)\text{ or }0}}_{(+)\text{ or }0}+\underbrace{2\gamma^2(1+d)^3}_{(+)}+\underbrace{2(\beta+1)^2d^4p^4}_{(+)}+\underbrace{\gamma(1+d)^2d^2p^2\overbrace{\left(4-(\beta+1)^2\right)}^{(+)\text{ or }0}}_{(+)\text{ or }0}>0,$$

which holds given $0 < \beta < 1$, and $\gamma > 0$.

In addition, the total quantity produced in the case of no entry is larger than the total quantity produced in the case of entry if

$$q^{ne} > 2q^{ent},$$

$$\frac{(a-c)(\gamma(1+d)+d^2p^2)}{2d^2p^2+\gamma(d+1)^2} > \frac{2(a-c)\left((\beta+1)^2d^2p^2+2\gamma(d+1)\right)}{4(\beta+1)^2d^2p^2+4\gamma(d+1)^2},$$

which simplifies to,

$$\gamma(1+d)p^2d^2(d-1)(2-(\beta+1)^2) > 0,$$

which holds if $2-(\beta+1)^2 > 0$, or $\beta < \sqrt{2}-1$.

4.4. Numerical proof of Lemma 1.

The social welfare in the case of entry (SW^{ent}) is:

$$SW^{ent} = \frac{(a-c)^2\left((\beta+1)^4d^3(3d-1)p^4+(\beta+1)^2\gamma d^2(d+3)(3d+1)p^2+4\gamma^2(d+1)^3\right)}{8\left((\beta+1)^2d^2p^2+\gamma(d+1)^2\right)^2} - F.$$

When there is no entry, the social welfare (SW^{ne}) is:

$$SW^{ne} = \frac{(a-c)^2\left(d^3(3d-1)p^4+\gamma d^2(d(d+6)+1)p^2+\gamma^2(d+1)^3\right)}{2\left(2d^2p^2+\gamma(d+1)^2\right)^2}.$$

Because of the fixed cost of entry and complex nature of the functions, the analytic comparison of the social welfare in each case is done numerically and the results are shown in Figure 3 and explained in the main text of the paper.

4.5. Comparison to Poyago-Theotoky (2007)

We compare the equilibrium values in the case of entry to the equilibrium values in the non-cooperative case in P-T, specifically equations (4), (5), and (6) in P-T. To make the comparisons, we assume that $p=1$.

First, we come the level of investment in abatement z (the equilibrium values from P-T will be denoted by the superscript PT):

$$z^{ent} = \frac{(\beta+1)(d-1)(a-c)d}{2d^2(\beta+1)^2+2\gamma(d+1)^2},$$

$$z^{PT} = \frac{(a-c)((\beta+1)d+(2d-1)(d+1))}{(\beta+1)d(3(\beta+3)+(\beta+7)d)+2\gamma(d+1)^2}.$$

Unfortunately, this does not simply into a form that is easier to interpret, so the graphical analysis is presented in figure 4.

We can, however, compare the total amount of abatement in each framework and find that there is always more abatement in the P-T framework:

$$(1+\beta)z^{ent} < 2(1+\beta)z^{PT}.$$

The next comparison is that of the tax rates:

$$t^{ent} = \frac{(a-c)\left(2\gamma\left(2d^2+d-1\right)+(\beta+1)^2d^2p^2\right)}{4(\beta+1)^2d^2p^2+4\gamma(d+1)^2} > \frac{(a-c)\left(2\gamma\left(2d^2+d-1\right)+(\beta+1)^2(2d-3)d\right)}{2(\beta+1)d(3(\beta+3)+(\beta+7)d)+4\gamma(d+1)^2} = t^{PT}.$$

The final comparison is that of the quantity produced:

$$q^{ent} = \frac{(a-c)\left((\beta+1)^2d^2p^2+2\gamma(d+1)\right)}{4(\beta+1)^2d^2p^2+4\gamma(d+1)^2} < \frac{(a-c)((\beta+1)d(3\beta+4d+7)+2\gamma(d+1))}{2(\beta+1)d(3(\beta+3)+(\beta+7)d)+4\gamma(d+1)^2} = q^{PT}.$$

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