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Green products, market structure, and welfare

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Abstract
This paper examines the welfare consequences of private provision of green goods in output markets with product differentiation. In our setting, consumers can be prone to engage in the consumption of green goods (e.g., from eco-labels or due to some forms of altruism), and firm entry is endogenous. Our analysis shows that firms underinvest in environmentally cleaner products in situations where the social damage from polluting emissions is sufficiently large. However, beyond those situations, we find that firms can underinvest or overinvest depending on effects mediated through firm entry because entry raises output and thus increases consumer participation in the market, but it also reduces private incentives to provide consumers with cleaner products.

Keywords Green products · Polluting emissions · Market structure

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1 Introduction

In recent decades, both the consumption and the production of green goods have been a topic of increasing interest in the economics literature as well as in politics. One of the main reasons is that green goods are environmentally cleaner products

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that can reduce pollution and waste. Based on that, governments have adopted policies such as taxes and subsidies, public campaigns, education, and performance standards in order to increase the consumption of green goods and also to encourage firms to invest in the production of those goods (e.g., see OECD 2008).

A basic argument behind those policies is that production can lead to externalities that induce governments to promote green goods. For example, in the case of polluting emissions which those goods tend to reduce, one such policy consists of taxes. According to classical environmental economics, we know that Pigouvian taxes can be socially useful in the face of welfare effects from emissions not entirely internalized by agents. To the extent that output implies emissions, a tax per unit of output can work as if the firms' marginal production costs had increased and then a lower level of output, and thus of emissions, is induced. In the context of green products, however, the issue also includes the firms' investment in green production and the consumers' willingness to pay for green products. Additionally, many green goods are produced under product differentiation, which can contribute to imperfect competition in the product market (Schinkel and Spiegel 2017) and can affect the firms' incentives to enter the industry. The empirical evidence in Wu (2009) documents that firms' strategies can, in fact, lead to an excessive provision of green goods in some situations. As is shown by Espínola-Arredondo and Muñoz-García (2016) for an exogenous market structure, the observation of insufficient green investments at an aggregate macroeconomic level does not prevent that they can be excessive in microeconomic contexts of relevant industries.

In this paper, we attempt to contribute to a better understanding of linkages between the private provision of green goods and market structure under imperfect competition and endogenous firm entry. In our setting, consumers' willingness to pay for (environmentally cleaner) green goods allows for internalizing a fraction of externalities from production (e.g., polluting emissions), stimulates the firms' investments in cleaner products, and ends up affecting equilibrium profits and thus firm entry. However, in our analysis consumers' willingness to pay for green goods does not imply that the private provision of those goods is a first-best provision, even if that willingness to pay is relatively high.[1]

The literature has shown that imperfect competition in output markets can be relevant in a variety of environmental issues. Among other aspects, previous contributions have examined the role of taxes on the average environmental quality consumed (e.g., Cremer and Thisse 1999), eco-labels (Kuhn, 1999, and Clemenz 2010), green consumerism (Eriksson 2004, and Conrad 2005), and price competition with some forms of product differentiation (Rodríguez-Ibeas 2007; Garcia-Gallego and Georgantzis 2009, and Espínola-Arredondo and Zhao 2012). A common assumption in most of this literature is the absence of firm entry, whereas we consider firm entry as endogenous.

Previous work with endogenous market structure suggests that firm entry can be important in the context of environmental economics. That literature includes the work by Katsoulacos and Xepapadeas (1995), who consider a Cournot oligopoly

[1] This is in line with previous work (e.g., Garcia-Gallego and Georgantzis 2009), although we find a non-monotonic pattern from free entry that differentiates our results.

model on environmental policy, as well as subsequent work that extends or qualifies these authors' findings.[2] Our focus on consumer willingness to pay for green goods reveals that private incentives to enter an industry can affect social welfare in the presence of emissions through a number of new effects relative to previous work. In order to identify those effects in a unified framework, we consider monopolistic competition with the spokes model by Chen and Riordan (2007), which extends the conventional Hotelling model of spatial product differentiation to an arbitrary number of firms.[3] One of the advantages of this setting is that monopolistic instead of perfect competition yields the limiting configuration when the number of firms becomes large, in contrast with oligopoly models such as Cournot. This feature is particularly appealing in environmental issues such as pollution that can affect many consumers and producers.[4]

Our results suggest that market structure can affect the equilibrium level of green output and thus of emissions, so that the level of green production may be insufficient or excessive relative to the socially optimal level. The reason is that entry may have two contradictory effects on social welfare. On the one hand, aggregate output rises and increases the participation of consumers in the market. On the other, the average green content of the goods provided to consumers declines (e.g., emissions increase). This yields two inefficiencies in our setting: first, some monopoly power on the firms' side from product differentiation and consumer lock-in for those consumers who can only buy from one firm; second, insufficient or excessive investments in the environmental quality of the goods in the presence of environmental externalities that are not fully internalized by the consumers. Therefore, the assumption in most of the policies adopted by governments that green production should be always promoted must not be taken for granted without further study, particularly when both firm entry and the investment in green production are costly.

[2] Katsoulacos and Xepapadeas (1995) consider a homogeneous-product Cournot oligopoly. Simpson (1995) extends their findings to an asymmetric duopoly, whereas Yin (2003) deals with an inter-firm pollution externality. Lahiri and Ono (2007) show that free entry can also affect the comparison of policy instruments such as a relative emission standard and emission taxes. An analysis with product differentiation can be found in Katsoulacos and Xepapadeas (1996) in the absence of firm entry, and in Petrakis et al. (1999) in its presence. See Fujiwara (2009) for a more recent model of differentiated-product oligopoly with free entry. In a related vein, see also Breton and Sbragia (2020) for an interesting analysis of a differentiated Cournot oligopoly with two product varieties supplied by two asymmetric groups of firms with access to different technologies. In our analysis, each firm can choose the environmental content of its product by means of green investments based on technologies available to all the firms, and the number of product varieties is endogenous under monopolistic competition.

[3] Economic applications of the spokes model include Caminal (2010), Caminal and Granero (2012), Germano and Meier (2013), Granero (2013), Reggiani (2014), and Chen and Hua (2017). See Reggiani (2020) for an overview. Product quality is considered in Granero (2019) for a fixed number of firms (duopoly), whereas endogenous firm entry is a central item in our analysis.

[4] A key difference between the spokes model and other spatial models of imperfect competition, including the linear-city (Hotelling) model and the circle (Salop) model, is that competition is non-localized in the spokes model. This aspect leads to new results in the original spokes model that are related to firm entry (e.g., results on pricing), and it also allows for Chamberlinian monopolistic competition without losing the spatial foundation for product differentiation. Older settings (e.g., Dixit and Stiglitz 1977) used to account for monopolistic competition without the advantages of spatial product differentiation (Sutton 1991, 1998).

A key feature in our analysis is that the relative weight of those two contradictory effects of firm entry on welfare will depend on consumers' willingness to pay for green goods. The reason is that this willingness to pay leads to partial internalization of the overall negative externalities from production. In fact, the available empirical evidence documents that consumers' willingness to pay an extra premium for sustainable products has increased over recent decades, perhaps due to subjective sustainable consumerism or to objective attributes of environmentally cleaner goods (Kahn 2007). Complementarily, microeconomic theory suggests a kind of altruism as a plausible rationale for sustainable consumption, according to which consumers partially internalize the overall welfare impact of emissions (e.g., see Andreoni 1990; Bergstrom 1995; Popp 2001; Bagnoli and Watts 2003; Garcia-Gallego and Georgantzis 2009, and Schinkel and Spiegel 2017). We rely on this literature in considering the presence of consumers who are willing to pay an extra premium for green goods. In our results, mediated through firm entry, this plays a key role in determining private incentives that lead to an excessive or insufficient level of green output and thus of emissions relative to the first-best level when green production imposes costs on firms.

In our analysis, we study end-of-pipe abatement technologies that are conventional both in practice and in the related literature.[5] For exogenous market structures, Clemenz (2010) shows that underinvestment in these technologies is likely to occur even with environmentally aware consumers. Here, we find that a non-monotonic pattern of underinvestment and overinvestment can take place when market structure is endogenous. In particular, when the negative externality from emissions is sufficiently large, there is excessive firm entry, so that private incentives yield underinvestment in green production and an excessive level of emissions relative to the economic first best. Under such circumstances, some effective policies resemble traditional instruments such as Pigouvian taxes. This contrasts with situations where the environmental externality is not so large. Specifically, in the presence of firm entry and costly investment in green production, we find a non-monotonic pattern with underinvestment or overinvestment due to several effects identified in our analysis. Then, in situations with insufficient firm entry there will be overprovision of the extent to which products are green, and some effective policies resemble subsidies (which stimulate firm entry) rather than taxes.

The rest of the paper is as follows. Section 2 introduces the model and the welfare benchmark. Then, Section 3 examines monopolistic competition and the free-entry equilibrium, and Sect. 4 compares the equilibrium and the socially optimal configurations. The proofs of the results are in the Appendix.

[5] Among others, see Bansal and Gangopadhyay (2003), and Clemenz (2010). End-of-pipe technologies are characterized by the fact that they leave the production process itself unchanged, but a fraction of the pollutant is reduced or offset. A Google search for "end-of-pipe technology" returned 270 million results in September 2020. Well-known examples include catalytic convertors on automobile tailpipes, scrubbers to control SO_2 emissions, membrane technologies used for wastewater treatment, and air cleaning devices.

2 Model

2.1 Product variety

We consider a product market with N potential varieties spatially differentiated as in the spokes model by Chen and Riordan (2007). The spokes model can be seen as a generalization of the Hotelling model of spatial product differentiation with an arbitrary number of product varieties and firms. In particular, starting at the midpoint of a line of unit length, other lines of one-half length can be added to form a radial network of N lines (spokes). We adopt the convention that each spoke terminates at the central point of the network and originates at the other end. In the spatial representation of the market, the spokes network is such that each potential variety i is located at the origin of spoke i, for $i = 1, \ldots, N$. Each potential variety may or may not be supplied. Specifically, there are $n \leq N$ firms in the product market, and each firm produces a different variety of the product, with the producer of variety i located at the origin of spoke i. In addition, there is a continuum of consumers with mass $N/2$ uniformly distributed over the N spokes. Each consumer must travel to a firm in order to purchase the firm's brand, and incurs transportation costs or, alternatively, utility losses from imperfect preference matching. As is standard, consumer location represents the relative valuation of two varieties. For a consumer located on spoke i, brand i is her first preferred brand, and each of the other $N - 1$ brands is equally likely to be her second preferred brand, say brand j. The consumer has value v_i for one unit of her first preferred brand, value v_j for one unit of her second preferred brand, and zero value for other brands. Because each consumer derives utility from two varieties and the probability of all pairs is the same, the mass of consumers who have a taste for variety i is 1, and the mass of consumers with a taste for varieties i and j is $1/(N-1)$ for all $j \neq i$.

The setting can be simplified by treating the number of active firms as a continuous variable (Chen and Riordan 2007; Caminal and Granero 2012). To that end, we denote the fraction of active varieties (firms) by $\gamma \in [0, 1]$, which is treated as a continuous variable by considering the limit as N goes to infinity and expressing relevant variables relative to the total mass of consumers. Because each particular firm may or may not enter the market, consumers can be classified into three different groups depending on whether their preferred varieties are supplied or not when $0 < \gamma < 1$: for some consumers, their first and second preferred varieties will be supplied; for some other consumers, only one of their preferred varieties will be supplied; and finally for the remaining consumers none of their preferred varieties will be supplied. Given γ and N, the number of pairs of varieties for which two suppliers are active is $\gamma N(\gamma N - 1)/2$, and since the fraction of consumers with a taste for a particular pair is $2/(N(N-1))$, then the fraction of consumers with access to two varieties is $\gamma N(\gamma N - 1)/(N(N-1))$. Hence, the fraction of consumers with access to a pair of active varieties is γ^2 as N goes to infinity. Similarly, the fraction of consumers with access to only one active variety is $2\gamma(1-\gamma)$, and the fraction of consumers with access to no active variety is $(1-\gamma)^2$ as N goes to infinity. From the viewpoint of supplier i, the fraction of consumers that demand variety i and have the opportunity of choosing between brand i and another brand is $(\gamma N - 1)/(N - 1)$, which tends to γ as N goes to infinity. Analogously, the fraction of consumers that demand brand i without access to a different brand is $1 - \gamma$ in the limit as N goes to infinity.

Some specific aspects of consumers and firms in the presence of environmental product quality follow in turn.

2.2 Consumers

Each consumer must travel on the spokes to reach any firm where she wishes to purchase the product, incurring positive transportation costs. This means that, based on their different locations, consumers are heterogeneous with respect to their relative valuations of brands. Specifically, a consumer located at $x \in [0, 1/2]$ on spoke i with a taste for varieties i and j will either incur a transportation cost of x if she buys i or a transportation cost of $(1 - x)$ if she buys j (the unit transportation cost is normalized to unity). Then, the consumer will obtain a surplus of $v_i - x - p_i$ if she buys brand i at the price p_i, and a surplus of $v_j - (1 - x) - p_j$ if she buys brand j at the price p_j. In our analysis, the environmental quality of brands contributes to consumers' utility, so that v_i and v_j depend on the environmental features of brands i and j, respectively. In particular, $v_i > v_j$ whenever brand i is greener than brand j (and analogously for $v_i \leq v_j$). In that sense, consumers' utility increases with the green or ecological dimension of the good that they buy. This can follow from subjective green consumerism or from objective attributes of environmentally cleaner goods (e.g., see Bansal and Gangopadhyay 2003, and Clemenz 2010). Under such circumstances, we write $v_i = v - \theta e_i$ and $v_j = v - \theta e_j$ for the preferred varieties i and j, where v is each consumer's gross value for one unit of her first or second preferred varieties, e_i and e_j are the emission levels from the production of those varieties, and θ is the consumer's marginal disutility from a higher level of emissions.[6] For her preferred pair of product varieties, each consumer will purchase the variety that provides her with the highest net surplus, subject to variety availability.

2.3 Producers

The production of each variety involves a marginal cost c. In addition, the production process implies a zero-abatement emission level of e_0 per unit of output. To reduce emissions, each producer i can make use of a standard end-of-pipe abatement technology that leaves the production process itself unchanged, but a

[6] Because lower levels of emissions lead to higher levels of environmental product quality, our framework can accommodate main effects from eco-labels in the presence of green consumers (e.g., see Clemenz (2010), and Espínola-Arredondo and Zhao, 2012). In parallel, the impact of lower emission levels on consumers' utility in our framework is similar to the role of certification of corporate social responsibility in Garcia-Gallego and Georgantzis (2009), and Manasakis et al. (2013). In that context, θ can be indicative of the consumer's degree of altruism.

fraction of the pollutant is reduced or offset by appropriate measures.[7] Specifically, firm i is able to reduce emissions and reach a level e_i at the cost $\beta(e_i)$ per variety produced. For each firm i, the cost function $\beta(\cdot)$ is strictly convex, with $0<\beta(e_i)<\infty$, $-\infty<\beta'(e_i)<0$ for $e_i \in [0, e_0)$; $\beta(e_i)=0$, $\beta'(e_i)=0$ for $e_i \geq e_0$, where e_0 is the firm's emission level per unit of output with no abatement. In considering these assumptions, we follow the previous literature on the adoption of end-of-pipe technologies (e.g., see Amacher and Malik 2002; Bansal and Gangopadhyay 2003, and Clemenz 2010).[8] From an economic standpoint, end-of-pipe technologies can be particularly relevant under firm entry because they lead to endogenous sunk costs (see Sutton 1991, 1998, and Clemenz 2010, among others). Then, producing each brand i involves a total fixed cost $F_i = f + \beta(e_i)$, where $f > 0$, and the total amount of fixed costs per consumer is given by $\gamma NF_i/(N/2) = 2\gamma F_i$.

2.4 Welfare benchmark

We consider a welfare function given by $W = CS + \Pi - D$, where CS stands for consumer surplus, Π for industry profits, and D for the aggregate damage due to an environmental externality from emissions. In our analysis, as in most of the previous related literature, each firm can be seen as producing two items: the firm's brand (an economic good) and a pollution output (an economic bad), so that one unit of each variety i of the good requires a level of emissions denoted by e_i, and the lack of a market for the pollution output gives rise to a negative externality from emissions (e.g., see Kolstad 2010). In our setting, we write the aggregate damage from emissions as $D = \lambda E$, where λ is a parameter that captures the marginal economic externality from the damage of emissions, and E is the aggregate level of emissions (total pollution output).

Consumers' willingness to pay for the good depends on the level of emissions required to produce the good because those emissions determine the environmental quality of the good. Since this affects the effective externality from emissions, some of the previous literature refers to $CS - D$ as consumer welfare (e.g., see Bansal and Gangopadhyay 2003). In that context, the marginal effective harm in welfare from environmental wastes or emissions is given by $\theta_w \equiv \theta + \lambda$. A sufficient condition to obtain interior solutions in the analysis below is $\beta''(e) > \theta_w^2/4$ for $e \in [0, e_0)$, which we assume hereafter. Additionally, we assume $v > 3 + c + \theta_w e_0$ so that producers

[7] A Google search for the keywords "end-of-pipe technology" returned 270 million results, and "end-of-pipe treatment" returned 98 million results in September 2020. Examples include catalytic convertors on automobile tailpipes, scrubbers to control SO_2 emissions, membrane technologies used for wastewater treatment, and air cleaning devices that separate air pollutants and GHGs from the post-combustion gases. Among others, see Fatta-Kassinos et al. (2016) for membrane technologies, which are the most powerful technologies for removing key microcontaminants; Tan (2014) for an introduction to end-of-pipe treatments for air emissions; and Hlavinek et al. (2010), Kumar et al. (2017), and Singh and Singh (2019) for end-of-pipe wastewater treatment and biotechnologies.

[8] With e_i as a continuous variable, the setting is able to capture the host of real-world technological combinations available from waste capture, separation and storage, and from combinations of materials in end-of-pipe technologies (e.g., see Clemenz 2010; Olajire 2010; Favre 2011, and Wang et al. 2011).

want to serve as many consumers as possible for any given number of active varieties, thus preventing that firms perform as local monopolies.

In the Appendix, we show that the economic welfare benchmark can be written as

$$W = \gamma^2\left(v - \theta_w e - \frac{1}{4} - c\right) + 2\gamma(1-\gamma)\left(v - \theta_w e - \frac{1}{2} - c\right) - 2\gamma(f + \beta(e)). \quad (1)$$

At an economic first-best configuration, the social planner will maximize $W(\gamma, e)$ in this expression. The first-order conditions yield[9]

$$\frac{1}{4}\gamma + (1-\gamma)\left(v - \theta_w e - \frac{1}{2} - c\right) = f + \beta(e), \quad (2)$$

$$-\beta'(e) = \frac{2-\gamma}{2}\theta_w. \quad (3)$$

These equations are standard in previous contributions in related contexts (e.g., see Caminal and Granero 2012, and Granero 2019). Here, given $\gamma \in (0,1)$, equation (3) yields the optimal level of emissions as increasing in γ. At the optimal solution, the marginal cost from investment in green production per consumer, $-2\gamma\beta'(e)$, must equal the marginal increase in consumer surplus for the fraction of consumers with access to the product, $(\gamma^2 + 2\gamma(1-\gamma))\theta_w = \gamma(2-\gamma)\theta_w$. Consequently, at the optimal solution $-2\gamma\beta'(e) = \gamma(2-\gamma)\theta_w$, which leads to (3) for $\gamma \in (0,1)$. Since $0 \leq \gamma \leq 1$, we can define the boundary values of e from (3) as $\underline{e}_w$ and $\overline{e}_w$ such that

$$-\beta'(\underline{e}_w) = \theta_w, \; -\beta'(\overline{e}_w) = \theta_w/2. \quad (4)$$

The following results account for the optimal values γ^w and e^w and for comparative statics. The proofs of the results are in the Appendix.

Proposition 1 *Define* $\underline{f}_w \equiv \frac{1}{4} - \beta(\overline{e}_w)$ *and* $\overline{f}_w \equiv v - \theta_w \underline{e}_w - \frac{1}{2} - c - \beta(\underline{e}_w)$. *Then, (i)* $\gamma^w = 0$ *for* $f \geq \overline{f}_w$; *(ii)* (γ^w, e^w) *is given by the solution to (2) and (3) for* $f \in [\underline{f}_w, \overline{f}_w]$; *(iii)* $(\gamma^w, e^w) = (1, \overline{e}_w)$ *for* $f \leq \underline{f}_w$.

Proposition 2 *Both* γ^w *and* e^w *are weakly decreasing in f, and strictly decreasing in f for* $f \in (\underline{f}_w, \overline{f}_w)$.

3 Monopolistic competition

In this section, we examine the free-entry equilibrium from monopolistic competition as a decentralized configuration, where each firm in the output market produces one variety. If firm i enters the market then it pays a cost $f + \beta(e_i)$ with a level of emissions e_i, and it sets a price p_i to maximize profits. Firms maximize

[9] In maximizing total surplus, it does not matter whether γ and e are decided sequentially or simultaneously. Second-order conditions for an interior solution hold under the maintained hypothesis (see Granero 2019).

profits and enter the market only if net profits are positive. We focus on symmetric free-entry equilibria.

Let us first deal with the price and the level of emissions, for a given number of firms (which will be determined from firm entry below). In market segments where consumers have access to two varieties, they will choose supplier as in the Hotelling model, and then a consumer will be indifferent between buying from firm i or from another firm that chooses a price p and a level of emissions e when

$$v - \theta e_i - x - p_i = v - \theta e - (1 - x) - p, \tag{5}$$

from where the distance x yields the fraction of consumers that choose firm i:[10]

$$x = \frac{1}{2} + \frac{\theta(e - e_i) + p - p_i}{2}. \tag{6}$$

In market segments where firm i's product is the consumers' only choice, total demand is 1 whenever consumers obtain a positive surplus. For our maintained hypothesis ($v > 3 + c + \theta_w e_0$) firms have incentives to serve as many consumers as possible, that is, they never find it optimal to set p_i and e_i such that their price is above $v - \theta e_i - 1$ (see Appendix, proof of Proposition 3). Hence, firm i decides on p_i and e_i in order to maximize:

$$\pi_i = \left[\gamma\left(\frac{1}{2} + \frac{\theta(e - e_i) + p - p_i}{2}\right) + 1 - \gamma\right](p_i - c) - \beta(e_i) - f, \tag{7}$$

subject to $p_i + \theta e_i \leq v - 1$. If this constraint is not binding,

$$\frac{\partial \pi_i}{\partial p_i} = \gamma\left(\frac{1}{2} + \frac{\theta(e - e_i) + p - 2p_i + c}{2}\right) + 1 - \gamma, \tag{8}$$

$$\frac{\partial \pi_i}{\partial e_i} = -\frac{\gamma\theta}{2}(p_i - c) - \beta'(e_i), \tag{9}$$

from where the optimal price and level of emissions are determined by[11]

$$p_i = \frac{2 - \gamma}{2\gamma} + \frac{\theta(e - e_i) + p + c}{2}, \tag{10}$$

$$-\beta'(e_i) = \frac{\gamma\theta}{2}(p_i - c), \tag{11}$$

The symmetric equilibrium price, $p_i = p = p^*$, and level of emissions, $e_i = e = e^*$, are then given by

$$p^* = c + \frac{2 - \gamma}{\gamma}, \tag{12}$$

[10] Provided $p_i \in [\theta(e - e_i) + p - 1, \theta(e - e_i) + p + 1]$, so that $0 \leq x \leq 1$.

[11] See Appendix, proof of Proposition 3, for details on second-order conditions.

$$-\beta'(e^*) = \frac{2-\gamma}{2}\theta. \tag{13}$$

From (13), define $\underline{e}$ and $\overline{e}$ analogously to the thresholds $\underline{e}_w$ and $\overline{e}_w$ in (4):

$$-\beta'(\underline{e}) = \theta, \quad -\beta'(\overline{e}) = \theta/2. \tag{4'}$$

The equilibrium is given by (12–13) provided $p^* + \theta e^* < v - 1$, which is equivalent to $\gamma > \frac{2}{v - \theta e^* - c}$. For brevity, a threshold $\widehat{\gamma}$ can be introduced to write this condition as $\gamma > \widehat{\gamma}$ hereafter.[12]

Furthermore, if $p^* + \theta e^* < v - 2$, an individual firm i may find it optimal to deviate from $p^* + \theta e^*$ and set $p_i + \theta e_i = v - 1$. Such a deviation is not profitable provided:

$$v - c \leq 1 + \frac{(2-\gamma)^2}{2\gamma(1-\gamma)} + \theta e^*(\gamma). \tag{14}$$

If this condition does not hold, a symmetric equilibrium does not exist.[13]

Hence, provided $\gamma \in [\widehat{\gamma}, 1]$ the mass of active firms in equilibrium, γ^*, will be given by the zero profit condition:

$$\pi^*(\gamma^*) = \frac{(2-\gamma^*)^2}{2\gamma^*} - \beta(e^*(\gamma^*)) - f = 0. \tag{15}$$

Equivalently, if $f \in [\underline{f}, \widehat{f}]$ then (provided condition (14) holds) $\gamma^*(f)$ is given by the solution to (15), and if $f \leq \underline{f}$ then $\gamma^* = 1$, where $\underline{f} \equiv \frac{1}{2} - \beta(\overline{e})$, and $\widehat{f}$ is defined as the value of f such that $\pi^*(\widehat{\gamma}) = 0$ in equation (15).

If instead $\gamma \leq \widehat{\gamma}$, which occurs whenever $f \geq \widehat{f}$, each firm faces little competition and finds it optimal to set $p^* + \theta e^* = v - 1$, and serve all consumers with no other choice. Then, each firm's profits are

$$\pi_i = \frac{2-\gamma}{2}(v - \theta e_i - 1 - c) - \beta(e_i) - f, \tag{16}$$

so that

$$p^* = v - \theta e^* - 1, \tag{17}$$

$$-\beta'(e^*) = \frac{2-\gamma}{2}\theta, \tag{18}$$

where (18) is as (13) above. In this case, the zero profit condition is:

[12] For example, with a quadratic green cost $\beta(e_i) = (e_0 - e_i)^2/2$ for $e_i \in [0, e_0)$ with $e_0 \geq \theta$, it follows that $\widehat{\gamma} = \{v - \theta(e_0 - \theta) - c - [(v - \theta(e_0 - \theta) - c)^2 - 4\theta^2]^{1/2}\}/\theta^2$.

[13] On the right-hand side of equation (14), notice that the function $\Psi(\gamma) \equiv 1 + \frac{(2-\gamma)^2}{2\gamma(1-\gamma)}$ reaches a minimum at $\gamma = \frac{2}{3}$, where $\Psi\left(\frac{2}{3}\right) = 5$, and e^* increases with γ.

$$\pi^*(\gamma^*) = \frac{2-\gamma^*}{2}(v - \theta e^*(\gamma^*) - 1 - c) - \beta(e^*(\gamma^*)) - f = 0. \tag{19}$$

Consequently, if $f \in [\widehat{f}, \overline{f}]$ then $\gamma^*(f)$ is given by the solution to (19), and if $f \geq \overline{f}$ then $\gamma^* = 0$, where $\overline{f} \equiv v - \theta \underline{e} - 1 - c - \beta(\underline{e})$.

This discussion is summarized as follows:

Proposition 3 *Define* $\underline{f} \equiv \frac{1}{2} - \beta(\overline{e})$ *and* $\overline{f} \equiv v - \theta \underline{e} - 1 - c - \beta(\underline{e})$. *Then, (i)* $\gamma^* = 0$ *for* $f \geq \overline{f}$*; (ii)* (γ^*, p^*, e^*) *is given by the solution to (17), (18) and (19) for* $f \in [\widehat{f}, \overline{f}]$*; (iii)* (γ^*, p^*, e^*) *is given by the solution to (12), (13) and (15) for* $f \in [\underline{f}, \widehat{f}]$*; (iv)* $(\gamma^*, p^*, e^*) = (1, c+1, \overline{e})$ *for* $f \leq \underline{f}$.

Proposition 4 *(i)* p^* *is weakly increasing in f, and strictly increasing in f for* $f \in (\underline{f}, \overline{f})$*; (ii) both* γ^* *and* e^* *are weakly decreasing in f, and strictly decreasing in f for* $f \in (\underline{f}, \overline{f})$.

Intuitively, the impact of f on equilibrium emissions is mediated through the impact of firm entry on price, and of price on emissions. An increase in the entry cost f reduces net profit and thus firm entry. Because the equilibrium price decreases with the number of active firms, an increase in f turns out to increase the free-entry equilibrium price. Therefore, an increase in f reduces the number of active firms, a lower number of firms increases the equilibrium price, and a higher price reduces in turn the free-entry equilibrium level of emissions. Hence, γ^* and e^* decrease with f. At this point, recall that the welfare-maximizing counterpart values γ^w and e^w decrease with f as well.

4 Equilibrium vs. socially optimal provision of green products

This section compares the provision of green products that follows from the decentralized free-entry equilibrium and from the socially optimal configuration.

4.1 First best

In the analysis, we find three different scenarios depending on the environmental externality: a large, an intermediate, and a small externality. In line with previous contributions (e.g., see Bansal and Gangopadhyay 2003), the marginal externality on social welfare from emissions is captured by the difference between the effective marginal harm in total welfare and each consumer's marginal disutility from a higher level of emissions, as given by $\lambda = \theta_w - \theta$. Ceteris paribus, the greater this difference, the larger the externality from emissions. Then, we obtain the following result:

Proposition 5 *There exist thresholds* $\underline{\alpha}$ *and* $\overline{\alpha}$*, with* $0 < \underline{\alpha} < \overline{\alpha}$*, such that:*

(i) *With an exogenous number of firms, the equilibrium level of emissions is above the first-best level for all* $\lambda > 0$.

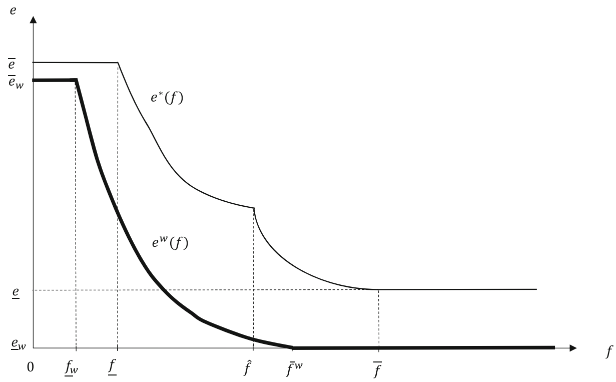

Fig. 1 Free-entry equilibrium vs. socially optimal emissions: large externality. [Example: $\beta(e) = (e_0 - e)^2/2, e_0 \geq \theta_w$]

(ii) *With an endogenous number of firms, there exist thresholds* f_I^a, f_I^b, f_{II}^a *and* f_{II}^b *, where* $f_{II}^a < f_{II}^b < f_I^a < f_I^b$*, such that:*

(iii) *if* $\lambda \geq \overline{\alpha}$ *(large environmental externality) then the equilibrium level of emissions is above the first-best level;*

(iv) *if* $\underline{\alpha} \leq \lambda < \overline{\alpha}$ *(intermediate environmental externality) then the equilibrium level of emissions is above the first-best level for* $f < f_I^a$ *and for* $f > f_I^b$*, and it is below the first-best level for* $f_I^a < f < f_I^b$*;*

(v) *if* $0 < \lambda < \underline{\alpha}$ *(small environmental externality) then the equilibrium level of emissions is above the first-best level for* $f < f_{II}^a$*, for* $f_{II}^b < f < f_I^a$ *and for* $f > f_I^b$*, and it is below the first-best level for* $f_{II}^a < f < f_{II}^b$ *and for* $f_I^a < f < f_I^b$*.*

The explanation of this result is as follows. Part (i) deals with a situation where the number of firms is given. Then, without firm entry, the presence of an externality from emissions leads to an excessive level of emissions relative to the socially optimal level. This outcome is immediate and can be seen as a baseline situation with which to compare situations with firm entry. Based on that, part (ii) arises as the main part in the result with an endogenous number of firms, and thus we deal with its economic explanation in detail.

In part (ii) of Proposition 5, let us first consider the case (ii.1). Here, the externality from emissions is large. Then, firms choose to underinvest in green production, which reduces the cost $F = f + \beta(e)$ and implies excessive firm entry. Consequently, the outcome becomes analogous to that from the baseline situation without firm entry, and the equilibrium level of emissions is above the welfare-maximizing level. Figure 1 illustrates this case.[14] In Fig. 1, the regular line represents free-entry equilibrium emissions, $e^*(f)$, and the bold line socially optimal

[14] Graphical representations that illustrate Proposition 5 contribute to gain intuition but must necessarily consider concrete functional forms of the cost from abatement efforts, although the result holds more generally for our assumptions about $\beta(\cdot)$ (see proof in the Appendix). Then, for the exclusive purpose of graphical representations that illustrate the result, we draw a concrete example given by $\beta(e) =$

emissions, $e^w(f)$. Since there is excessive firm entry with an excessive equilibrium level of emissions, this situation yields an insufficient green content of the product. Consequently, it is socially optimal to reduce the equilibrium level of emissions. In that context, several instruments can be used to achieve a fall in equilibrium emissions. For example, a conventional tax per unit of output could contribute to that aim. Because this tax works as if the firms' marginal production cost had increased, it impacts on price-cost margins and thus on the level of investment in green production. Then, under free entry a fall in effective price-cost margins due to the tax will reduce the number of active firms and the equilibrium level of emissions, which could end up placing the equilibrium configuration closer to the socially optimal one. Graphically, in Fig. 1, the tax could place the line that represents free-entry equilibrium emissions, $e^*(f)$, closer to the line that represents socially optimal emissions, $e^w(f)$.

When the externality from emissions is intermediate as in part (ii.2), the optimal regulation is no longer unconditional. Figure 2 illustrates this case. As in part (ii.1), if f is relatively low then there is excessive firm entry ($\gamma^* > \gamma^w$) and the equilibrium level of emissions is above the socially optimal level ($e^* > e^w$). However, if f is relatively high then there is insufficient entry ($\gamma^* < \gamma^w$) and the equilibrium level of emissions can fall below the socially optimal level ($e^* < e^w$). The latter situation (Region I in Fig. 2) contrasts with the case of small willingness to pay for sustainability (i.e., large externality) in part (ii.1) and with the baseline case in part (i). Specifically, as in traditional spatial models of localized competition (e.g., Salop 1979), if the entry cost is higher than a certain threshold then all firms are local monopolists, and the equilibrium number of firms is insufficient. In that case, each of the active firms will have an incentive to invest in green production because, first, there is little competition with a small number of active producers in the market and, second, now consumers are relatively willing to pay for sustainability. In Region I of Fig. 2, those two aspects induce firms to overinvest in green production and thus to reduce the level of emissions below the socially optimal level. In those circumstances, a tax per unit of output (which reduces the firms' incentives to enter the industry) could increase the distance between the equilibrium and the first-best emission levels. In contrast, if the entry cost is below a certain threshold then there is excessive entry and the firms' decisions are driven by business stealing because a sizable fraction of an entrant firm's customers is stolen from existing firms, given that many firms are already active. Private incentives to invest in green products are then altered so that the equilibrium level of emissions becomes excessive. Then, a tax per unit of output could contribute to place the equilibrium configuration closer to the socially optimal one.

Now, consider the case of a small environmental externality as in part (ii.3). Figure 3 illustrates this case. Here, for extreme values of f ($f \leq f_{II}^a$ and $f \geq f_I^a$), we have situations similar to those arising from an intermediate willingness to pay. If f is sufficiently low to support equilibrium values of γ close to one, then business

Footnote 14 continued

$(e_0 - e)^2/2$ for $e \in [0, e_0)$ with $e_0 \geq \theta_w$. This graphical example also helps compare our results with previous contributions that focus on quadratic costs (e.g., Garcia-Gallego and Georgantzis 2009).

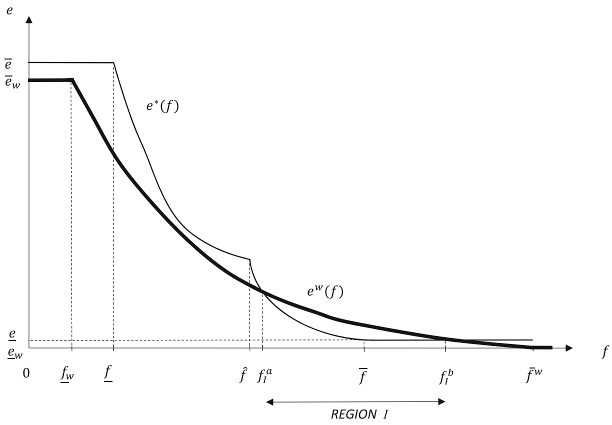

Fig. 2 Free-entry equilibrium vs. socially optimal emissions: intermediate externality. [Example: $\beta(e) = (e_0 - e)^2/2, e_0 \geq \theta_w$]

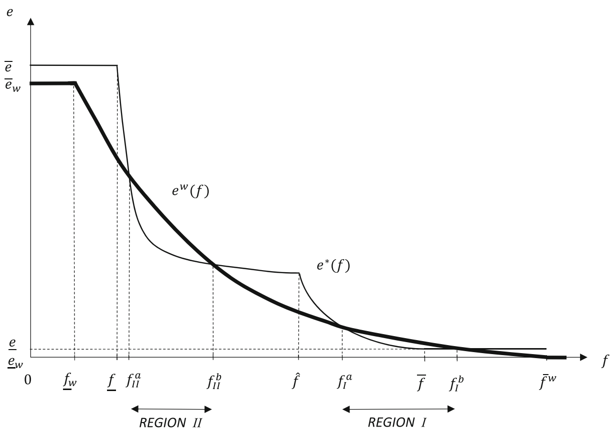

Fig. 3 Free-entry equilibrium vs. socially optimal emissions: small externality. [Example: $\beta(e) = (e_0 - e)^2/2, e_0 \geq \theta_w$]

stealing induces excessive firm entry, and the resulting equilibrium level of emissions ends up above the socially optimal level. If *f* is sufficiently high to support equilibrium values of γ close to zero, firms are close to being local monopolies and firm entry is insufficient, so that the equilibrium level of emissions falls below the socially optimal level for a relevant range of values of f ($f_I^a < f < f_I^b$). For the remaining situations ($f_{II}^a \leq f \leq f_I^a$) it is not obvious to determine the net effect of a change in *f* on the difference between equilibrium and first-best emission levels. As *f* decreases from levels that support equilibrium values of γ close to zero, then firm entry increases and business stealing intensifies. At a certain point, business stealing becomes the dominant effect and private incentives to enter become socially excessive, which leads to emissions above the welfare-maximizing level of emissions. If *f* falls so much that firm entry intensifies to the point that γ increases above the $\widehat{\gamma}$ (which is the mass of firms associated with $\widehat{f}$ in Fig. 3), then price competition intensifies considerably and private incentives to enter moderate thereafter. Since this limits the impact of business stealing for intermediate values of f, the equilibrium level of emissions can fall below the first-best level. This situation rests on the fact that consumers are very prone to pay for green products. The reason is that, in those circumstances (Region II, $f_{II}^{a} \leq f \leq f_{II}^{b}$), firms face a high degree of product-market competition (many firms have entered the market), which they can "relax" through green production (this becomes profitable due to the consumers' willingness to pay for sustainability). Consequently, we can have excessive or insufficient equilibrium levels of emissions. Graphically, for values of f in regions I and II of Fig. 3 the equilibrium level of emissions is insufficient (in contrast with the baseline case without firm entry), whereas for the rest of values of f the equilibrium level of emissions is excessive (as in that baseline case). Then, a tax per unit of output may or may not contribute, accordingly, to bringing the equilibrium configuration closer to the socially optimal one along the lines argued above.

4.2 Second best

To get an insight into the discussion above, briefly consider second-best configurations from Pigouvian taxes with the following timing. In the first stage, firms decide whether to enter the industry. Subsequently, in the second stage, the government chooses an environmental tax per unit of emissions, t, to maximize the welfare function $W = CS + \Pi - D + T$, where CS denotes consumer surplus, Π industry profits, D the aggregate damage due to the environmental externality from emissions, and T the tax revenue of the government. Finally, in the third stage, firms choose prices and environmental investments to maximize profits.

Proceeding backwards, consider the third stage in this timing. Given γ and t, each firm i decides on p_i and e_i to maximize:

$$\pi_i = \left[\gamma\left(\frac{1}{2} + \frac{\theta(e - e_i) + p - p_i}{2}\right) + 1 - \gamma\right](p_i - c) - te_i - \beta(e_i) - f, \qquad (20)$$

subject to $p_i + \theta e_i \leq v - 1$. Analogously to Sect. 3, here there exists a threshold $\widehat{\gamma}_{sb}$ such that in symmetric equilibrium ($p_i = p = p_{sb}^*$, $e_i = e = e_{sb}^*$), if $\gamma > \widehat{\gamma}_{sb}$ then $p_{sb}^* = c + (2 - \gamma)/\gamma$, whereas if $\gamma \leq \widehat{\gamma}_{sb}$ then $p_{sb}^* = v - \theta e_{sb}^* - 1$, and in these two cases

$$-\beta'(e_{sb}^*) = t + \frac{2 - \gamma}{2}\theta, \qquad (21)$$

where sb denotes the second-best configuration. This equation shows that, ceteris paribus, e_{sb}^* is decreasing in the environmental tax, t.

In the second stage, the government decides on the environmental tax by anticipating the impact of that tax on both p_{sb}^* and e_{sb}^*. Then, given γ, it can be seen that the optimal tax is:

$$t_{sb}^{*} = \frac{2-\gamma}{2}\lambda, \tag{22}$$

so that

$$-\beta'(e_{sb}^{*}) = \frac{2-\gamma}{2}\theta_w. \tag{23}$$

Making use of (3), this means that the equilibrium under the Pigouvian tax reproduces the first-best level of emissions for an exogenous market structure, i.e., $e_{sb}^{*}(\gamma) = e^{w}(\gamma)$ for given γ . As is conventional, the Pigouvian tax is able to remove any difference between private and social incentives in the determination of emissions when market structure is exogenous. In our analysis, with an endogenous market structure, whether this tax is actually a first-best policy will depend on the market structure that arises from firm entry. Under such circumstances, if market structure is determined by an efficient firm entry, the Pigouvian tax will be able to implement a first-best outcome. However, if firm entry is inefficient, then the Pigouvian tax will not implement the first-best configuration due to the Tinbergen rule: a single policy (here, the tax) will be insufficient to implement a first-best configuration when there are multiple market failures (in our case, the environmental externality and the possibility of excessive or insufficient firm entry).

In the first stage, market structure is endogenous and firms decide whether to enter the industry by anticipating the equilibrium values of t_{sb}^{*}, p_{sb}^{*} and e_{sb}^{*}. Then, each firm will decide to enter the industry whenever net profits are positive. Analogously to Sect. 3, there exists a threshold $\widehat{f}_{sb}$ such that if $f \in [\underline{f}_{sb}, \widehat{f}_{sb}]$ then the equilibrium mass of active firms, $\gamma_{sb}^{*}(f)$, will be given by a zero profit condition similar to equation (15), and if $f \leq \underline{f}_{sb}$ then $\gamma_{sb}^{*} = 1$, where $\underline{f}_{sb} \equiv \frac{1}{2} - \frac{\lambda}{2}\overline{e}_w - \beta(\overline{e}_w)$. If instead $f \in [\widehat{f}_{sb}, \overline{f}_{sb}]$, the zero profit condition is similar to equation (16), and if $f \geq \overline{f}_{sb}$ then $\gamma_{sb}^{*} = 0$, where $\overline{f}_{sb} \equiv v - \theta_w \underline{e}_w - 1 - c - \beta(\underline{e}_w)$.

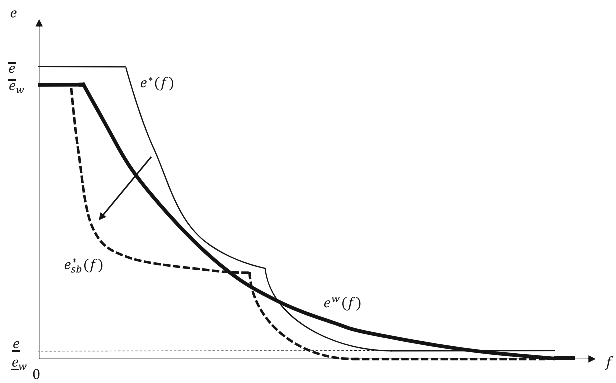

Fig. 4 Free-entry equilibrium vs. second-best optimal emissions: intermediate externality. [Example: $\beta(e) = (e_0 - e)^2/2, e_0 = 1.4, \theta = 0.6, \lambda = 0.7, v = 5, c = 0$]

To gain intuition, Figure 4 draws the impact of the Pigouvian tax on emissions for a numerical example of the case illustrated in Figure 2 (intermediate environmental externality, Proposition 5, case (ii.2)). At this point, recall that the tax reduces the firms' incentives to enter the industry (the introduction of the tax increases each firm's total costs). Based on that, the tax can be useful in bringing the equilibrium level of emissions closer to the first-best level when firm entry is excessive. Figure 4 shows that for intermediate values of f. However, in general that is not necessarily the situation that emerges from the tax. Even if firm entry is excessive in the absence of the tax, it may be the case that the tax discourages firm entry to the extent that entry becomes insufficient and the tax does not bring the equilibrium level of emissions closer to the first-best level. Then, firms can go into a kind of over-compliance with excessive green investments to avoid the environmental tax as much as possible. In general, the magnitude of this effect will depend on the environmental externality (Figs. 1, 2 and 3). Hence, the Pigouvian tax may or may not contribute to social welfare depending on the consumers' sensibility to the green dimension of goods and on the firms' incentives to enter the market, which points to the convenience of a combination of environmental taxes with other policies, such as eco-labels that can affect θ, or regulations that can affect f.

5 Concluding remarks

In this paper, we have explored the welfare consequences of private provision of green goods with product differentiation when consumers can be prone to engage in the consumption of green goods, green production is costly to firms but yields welfare externalities, and firms decide on end-of-pipe abatement and whether to enter the industry of the product.

Our analysis reveals that the interplay of green consumption and firm entry impacts on private incentives that determine the provision of green products in equilibrium. From this interplay, that private provision can be insufficient or excessive relative to the economic first best. In our setting, entry may have two contradictory effects on welfare. On the one hand, aggregate output rises and increases the participation of consumers in the market. On the other, the average green content of the product provided to consumers declines (e.g., emissions increase). Consumers' willingness to pay for green products determines the relative weight of these two effects because that willingness to pay allows for partially internalizing overall externalities from production such as emissions. Specifically, for extreme situations with many active firms or only a few of active firms, one of those two contradictory effects dominates and conclusions in terms of welfare tend to be unconditional. In contrast, for intermediate cases of firm entry the conclusions are less obvious without further study of the consumers' willingness to pay for green products and the environmental externalities.

Appendix

Welfare benchmark

Here, we derive the welfare benchmark in our analysis. The welfare function is written as $W = CS + \Pi - D$, where CS denotes consumer surplus, Π industry profits, and D the aggregate damage due to the environmental externality from emissions.

At a first-best configuration,

$$\begin{aligned}
CS &= \gamma^2\left(\int_0^{1/2}(v-\theta e-x-p)dx+\int_{1/2}^{1}(v-\theta e-(1-x)-p)dx\right)\\
&\quad+2\gamma(1-\gamma)\int_0^1(v-\theta e-x-p)dx\\
&=\gamma^2\left(v-\theta e-\frac{1}{4}-p\right)+2\gamma(1-\gamma)\left(v-\theta e-\frac{1}{2}-p\right),\\
\Pi &= 2\gamma\left(\frac{2-\gamma}{2}(p-c)-f-\beta(e)\right)=(2-\gamma)\gamma(p-c)-2\gamma(f+\beta(e)),\\
D &= \lambda E=\lambda(\gamma^2+2\gamma(1-\gamma))e=\lambda(2-\gamma)\gamma e,
\end{aligned}$$

from where

$$W=\gamma^2\left(v-\theta_w e-\frac{1}{4}-c\right)+2\gamma(1-\gamma)\left(v-\theta_w e-\frac{1}{2}-c\right)-2\gamma(f+\beta(e)),$$

with $\theta_w \equiv \theta+\lambda$, which gives W as in equation (1).

Proofs of the results

Proofs of Propositions 1 and 2 See Granero (2019). □

Proof of Proposition 3 From equations (8)–(9),

$$\begin{aligned}
&\frac{\partial^2\pi_i}{\partial p_i^2}=-\gamma<0,\quad \frac{\partial^2\pi_i}{\partial e_i^2}=-\beta''(e_i)<0,\\
&\frac{\partial^2\pi_i}{\partial p_i^2}\frac{\partial^2\pi_i}{\partial e_i^2}-\left(\frac{\partial^2\pi_i}{\partial p_i\partial e_i}\right)^2=\gamma\left\{\beta''(e_i)-\left(\frac{\theta}{2}\right)^2\gamma\right\},
\end{aligned}$$

where

$$\frac{\partial^2 \pi_i}{\partial p_i \partial e_i} = \frac{\partial^2 \pi_i}{\partial e_i \partial p_i} = -\frac{\gamma\theta}{2}.$$

Hence, $(\partial^2 \pi_i/\partial p_i^2)(\partial^2 \pi_i/\partial e_i^2) - \left(\partial^2 \pi_i/\partial p_i \partial e_i\right)^2 > 0$ iff $\beta''(e_i) > \gamma\theta^2/4$, which is implied by $\beta''(e_i) > \theta_w^2/4$ given that $\gamma \leq 1$ and $\theta \leq \theta_w$. Then, expressions (10) and (11) yield the profit-maximizing solution (p_i, e_i), and thus at a symmetric equilibrium $(p_i, e_i) = (p^*, e^*)$ as given by equations (12) and (13) for $f \in [\underline{f}, \widehat{f}]$, i.e., $\gamma \geq \widehat{\gamma}$, provided condition (14) holds. In those circumstances, free entry yields γ^* as the solution to the zero profit condition (15). For any $\gamma \geq \widehat{\gamma}$ that condition is equivalent to

$$g(\gamma) \equiv \gamma\pi^*(\gamma) = \frac{(2-\gamma)^2}{2} - \gamma\beta(e^*(\gamma)) - \gamma f = 0,$$

where $e^*(\gamma)$ follows from $-\beta'(e^*) = \theta(2-\gamma)/2$. We have that $g(\gamma)$ is a continuous function, $g'(\gamma) < 0$ when $\pi^*(\gamma) \geq 0$, $g(\widehat{\gamma}) > 0$ for $f < \widehat{f}$, and $g(1) \leq 0$. Hence, there exists one solution to $g(\gamma) = 0$ given by $\gamma^* \in (\widehat{\gamma}, 1)$. If $f = \widehat{f}$ then $\gamma^* = \widehat{\gamma}$ as given by

$$\frac{(v - \theta e^*(\widehat{\gamma}) - 1 - c)^2}{v - \theta e^*(\widehat{\gamma}) - c} - \beta(e^*(\widehat{\gamma})) = \widehat{f},$$

with $e^*(\widehat{\gamma})$ such that $-\beta'(e^*) = \theta(2-\widehat{\gamma})/2$; and if $f \leq \underline{f}$ then $\gamma^* = 1$.

Now, consider $f > \widehat{f}$, i.e., $\gamma < \widehat{\gamma}$. Here, we need to check that the only symmetric equilibrium involves $p^* = v - \theta e^* - 1$ and $-\beta'(e^*) = \theta(2-\gamma)/2$. A representative firm i chooses (p_i, e_i) to maximize

$$\pi_i = \left[\gamma\left(\frac{1}{2} + \frac{\theta(e - e_i) + p - p_i}{2}\right) + (1-\gamma)(v - \theta e_i - p_i)\right](p_i - c) - \beta(e_i) - f,$$

subject to $p_i + \theta e_i \geq v - 1$. The first-order conditions for an interior solution can be written as

$$\gamma(1 + \theta(e - e_i) + p - 2p_i + c) + 2(1-\gamma)(v - \theta e_i - 2p_i + c) = 0,$$
$$-\frac{\theta}{2}(2-\gamma)(p_i - c) - \beta'(e_i) = 0.$$

If a symmetric equilibrium exists, then the price is given by

$$p(\gamma) = \frac{2(1-\gamma)(v - \theta e(\gamma) + c) + \gamma(1+c)}{4 - 3\gamma},$$

where $e(\gamma)$ is such that

$$-\beta'(e) = \frac{\theta}{2}\frac{2-\gamma}{4-3\gamma}(2(1-\gamma)(v - \theta e - c) + \gamma).$$

It turns out that $p(0) + \theta e(0) = \frac{1}{2}(v + \theta e(0) + c) < v - 1$, and $p'(\gamma) < 0$. Thus, a contradiction follows. If other firms set $p + \theta e = v - 1$ then according to firm i's first-order conditions its best response is such that $p_i + \theta e_i = \frac{1}{2}(v + \theta e_i + c) < v - 1$. Therefore, the only symmetric equilibrium involves $p + \theta e = v - 1$, from where $p^* = v - \theta e^* - 1$ and $-\beta'(e^*) = \theta(2-\gamma)/2$. Then, free entry determines γ^* as the solution to the zero profit condition (19) if $f \in [\widehat{f}, \overline{f}]$, and $\gamma^* = 0$ if $f \geq \overline{f}$. This shows the result.

Proof of Proposition 4 Consider first $f \in (\underline{f}, \widehat{f})$. Then, γ^* is given by the solution to the zero profit condition (15). That condition is equivalent to

$$g(\gamma) \equiv \gamma\pi^*(\gamma) = \frac{(2-\gamma)^2}{2} - \gamma\beta(e^*(\gamma)) - \gamma f = 0,$$

where $e^*(\gamma)$ follows from $\beta'(e^*) = -\theta(2-\gamma)/2$. Hence, γ^* is given by the only solution to $g(\gamma) = 0$ such that $\gamma^* \in (\widehat{\gamma}, 1)$, and implicit differentiation gives rise to

$$\frac{d\gamma^*}{df} = -\frac{\gamma^*}{(2-\gamma^*)\left(1 - \frac{\theta^2}{4\beta''(e^*)}\gamma^*\right) + \beta(e^*) + f} < 0.$$

Next, consider that $f \in (\widehat{f}, \overline{f})$. Then, γ^* is given by the solution to the zero profit condition (19), and implicit differentiation yields

$$\frac{d\gamma^*}{df} = -\frac{2}{v - \theta e^* - 1 - c} < 0,$$

and if $f \geq \overline{f}$ then $\gamma^* = 0$. Thus, γ^* is weakly decreasing in f, and it is strictly decreasing in f for $f \in (\underline{f}, \overline{f})$. Since e^* is strictly increasing in γ for $f \in (\underline{f}, \overline{f})$, this implies that e^* is weakly decreasing in f, and it is strictly decreasing in f for $f \in (\underline{f}, \overline{f})$. Finally, because γ^* and e^* are strictly decreasing in f for $f \in (\underline{f}, \widehat{f})$, it follows that p^* is weakly increasing in f, and it is strictly increasing in f for $f \in (\underline{f}, \overline{f})$. Thus, the result is shown.

Proof of Proposition 5 With an exogenous number of firms, part (i) follows directly from equations (3), (12) and (13) under $\theta < \theta_w$. Next, with an endogenous number of firms it can be seen that there exists a positive threshold $\overline{\alpha}$ such that $\partial W(\gamma^*, e^*)/\partial e < 0$ for all $\lambda = \theta_w - \theta > \overline{\alpha}$. Hence, there exists no crossing point at which $e^*(\gamma^*) = e^w(\gamma^w)$ whenever the difference $\theta_w - \theta$ is above $\overline{\alpha}$. In particular, $e^*(\gamma^*) > e^w(\gamma^w)$ for all $\lambda > \overline{\alpha}$, so that part (ii.1) holds.

Consider now part (ii.2), so that $\lambda < \overline{\alpha}$. Here, there exists a positive threshold $\underline{\alpha} < \overline{\alpha}$ such that with $\lambda \in (\underline{\alpha}, \overline{\alpha})$ we have $\partial W(\gamma^*, e^*)/\partial e \gtreqless 0$ as $f \gtreqless f_I^a$ for $f \in [\underline{f}, \overline{f})$, and $\partial W(\gamma^*, e^*)/\partial e \lesseqgtr 0$ as $f \gtreqless f_I^b$ for $f \in [\overline{f}, \overline{f}_w]$. Consequently, in the region where $\widehat{f} \leq f \leq \overline{f}$ we can use equations (2) and (19) to see that as long as $\lambda < \overline{\alpha}$ there exists one crossing point at which $e^w(\gamma^w) = e^*(\gamma^*)$, where $e^w(\gamma^w)$ follows from (3), and $e^*(\gamma^*)$ follows from (13). However, in the region where $\underline{f} \leq f \leq \widehat{f}$ no crossing point at which $e^w(\gamma^w) = e^*(\gamma^*)$ does exist whenever $\lambda > \underline{\alpha}$. Hence, part (ii.2) follows.

Finally, consider part (iii.3), where $\lambda < \underline{\alpha}$. First, consider the region $\widehat{f} \leq f \leq \overline{f}_w$. Making use of (2) and (19), here γ^* and γ^w cross as long as

$$\frac{2-\gamma}{2}(v - \theta e^*(\gamma) - 1 - c) = \frac{1}{4}\gamma + (1-\gamma)\left(v - \theta e^w(\gamma) - \frac{1}{2} - c\right),$$

with $e^*(\gamma) = e^w(\gamma)$ for $\gamma = \gamma^* = \gamma^w$ under θ arbitrarily close to θ_w. This holds whenever

$$h_I(\gamma) \equiv \gamma\left(v - \theta e^w(\gamma) - \frac{1}{2} - c\right) - 1 = 0.$$

It can be seen that $h_I(0) < 0$, $h_I(1) > 0$, and $h'_I(\gamma) > 0$. Hence, in this region there exists one solution $\gamma \in (0,1)$ to $h_I(\gamma) = 0$. That is, there exists one crossing point at which $\gamma^* = \gamma^w$ when θ approaches θ_w. Denote that crossing point by $\gamma(f_I^a)$.

Next, consider the region $\underline{f}_w \leq f \leq \widehat{f}$. From (2) and (15), here γ^* and γ^w cross as long as

$$\frac{(2-\gamma)^2}{2\gamma} = \frac{1}{4}\gamma + (1-\gamma)\left(v - \theta e^w(\gamma) - \frac{1}{2} - c\right),$$

with $e^*(\gamma) = e^w(\gamma)$ for $\gamma = \gamma^* = \gamma^w$ under θ arbitrarily close to θ_w. This holds whenever

$$h_{II}(\gamma) \equiv 2\gamma(1-\gamma)\left(v - \theta e^w(\gamma) - \frac{1}{2} - c\right) + \frac{1}{2}\gamma^2 + (2-\gamma)^2 = 0.$$

We have that $h_{II}(0) < 0$, $h_{II}(1) < 0$, $h_{II}(\gamma) > 0$ for some $\gamma \in (0,1)$, and there exists a threshold value $\widetilde{\gamma} \in (0,1)$ such that $h'_{II}(\gamma) \gtreqless 0$ as $\gamma \lesseqgtr \widetilde{\gamma}$. Therefore, there is one root to $h_{II}(\gamma) = 0$ on the interval $(0, \widetilde{\gamma})$, and there is another root to $h_{II}(\gamma) = 0$ on the interval $(\widetilde{\gamma}, 1)$. Hence, here there exist two crossing points at which $\gamma^* = \gamma^w$ when θ approaches θ_w. Denote those crossing points by $\gamma(f_{II}^a)$ and $\gamma(f_{II}^b)$, where $f_{II}^a < f_{II}^b$. By continuity, this shows part (ii.3) and completes the proof.

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