An Excessive Development of Green Products?

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Abstract

This paper examines firms' incentives to develop a new (green) product, which might compete against the pollutant (brown) good that they traditionally sell. We show that in equilibrium more than one firm might develop a green product, but such an equilibrium outcome is not necessarily efficient. In particular, we predict an excessive amount of green goods under certain conditions, namely, when the green product is extremely clean but both products are not sufficiently differentiated in their attributes, and when the green product is not significantly cleaner than the brown good. We finally provide policies that help regulatory authorities promote equilibrium outcomes yielding the highest social welfare.

Keywords: Excessive entry; Product differentiation; Pollution intensity; Environmental damage.

JEL classification: L12, D82, Q20, D62.

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1 Introduction

In recent years, several firms have developed "green" product brands, in addition to the more polluting goods they traditionally produce. For instance, green house cleaners are nowadays common in most stores, e.g., Clorox produces Green Works in addition to its more conventional cleaners, such as Tilex and Pine-Sol.[1] Moreover, multiple car manufacturers, such as Toyota, Ford and Honda, not only offer their fossil-fuel cars but also (less polluting) hybrid cars. Furthermore, diaper companies have developed additional lines of products with better biodegradable properties, e.g., Huggies introduced Huggies Pure & Natural.[2] The development of these products is usually regarded as a desirable objective by the general public, and often supported with a myriad of public policies, such as subsidies and tax rebates. This paper, however, shows that firms' development of green products can become socially excessive in certain contexts.

Our model considers firms, competing in a Cournot duopoly, that initially produce a polluting good (brown product), and then decide whether to develop a green product. The brown and green goods differ both in their attributes and in their environmental features. A green good generates less pollution than a brown product, which can become zero when the good is sufficiently clean (low pollution intensity). In addition, a firm's development of the green product entails a positive effect on its profits, arising from selling a new green good; and a negative effect, from reducing sales of the brown good, given that both products compete when they are not sufficiently differentiated, i.e., business-stealing effect.[3]

We identify equilibrium outcomes in which either only one, both, or no firm develops the green product, depending on the investment costs that firms must initially incur in this enterprise. In addition, we show that as green and brown products become less differentiated, the development of the green product imposes a stronger negative effect on profits, thereby reducing firms' incentives to produce the green good. Hence, the equilibrium in which both (or one) firms develop the green good is only sustained under more restrictive parameter conditions. In contrast, when the green good is sufficiently differentiated, brown and green products are less likely to compete, and hence both firms voluntarily develop the green good.

We also evaluate the welfare properties of our equilibrium predictions, by separately considering the role of the pollution intensity of the green good and its degree of product differentiation with respect to the brown good. First, in the case in which the green product is completely clean and it is relatively differentiated, we find that the welfare arising when both firms develop the green good is larger than when only one firm (or none) develops it. As a consequence, our results suggest that regulators could lower the administrative costs that firms must incur in order to develop

[1] Similarly, Simple Green offers a separate brand, Simple Green Naturals, as "100% naturally derived, with ingredients originating from nature."

[2] More generally, among all newly introduced products in the U.S., the percentage that claimed to be green increased from 1.1% in 1986 to 9.5% in 1999; see Kirchoff (2000).

[3] Green products could in the long run replace brown products. However, the transition between these goods can still take several years, as the example of hybrid cars suggests. For instance, Toyota has simultaneously produced both the Toyota Prius and fossil-fuel cars since 1997.

a green plant (e.g., facilitate the acquisition of licenses, faster permits, etc.), thus promoting the presence of two firms in the green industry. This can be the case of goods that, besides being highly differentiated, exhibit significant environmental properties, such as electric cars with a substantially different performance to fossil-fuel cars.

While the above policy implication is in line with typical regulations on green markets, our findings show that lowering administrative and development costs is not necessarily welfare improving. In fact, our results recommend maintaining or increasing such costs under certain conditions. First, when products become more homogeneous, our findings indicate that the highest social welfare is actually attained if only one firm operates in the green industry. Hence, the regulator should in this setting maintain intermediate administrative costs in order to support a green monopoly. This policy recommendation would specifically apply for goods such as certain green cleaners which are undifferentiated relative to traditional cleaning products.

Second, if the green good, despite being cleaner than the brown product, exhibits a high pollution intensity, welfare is higher when no firm develops the relatively "dirty" green product than when one or both do, thus inducing a socially excessive development when costs are sufficiently low. Importantly, this result applies both when products are relatively differentiated and undifferentiated. Therefore, under certain conditions, the regulator would have incentives to increase the administrative costs in order to completely avoid the emergence of the green industry. Intuitively, this finding arises given the poor environmental performance of the green product.[4]

Standard models analyzing the development of new products consider firms producing a single good, and identify conditions under which development may become socially excessive; see Schmalensee (1978), Eaton and Lipsey (1979) and Mankiw and Whinston (1986). We find that development can also be excessive when firms simultaneously produce two goods that could compete against one another, thus giving rise to business-stealing effects (BSE). In addition, we allow for goods to exhibit different environmental properties. Relative to standard models in which BSE and environmental properties are absent, our findings suggest that excessive development is ameliorated. In particular, when BSE are present, firms develop new products under more restrictive conditions and, as a consequence, excessive development is less likely to emerge. Hence, while standard models predict excessive development under large conditions, and thus call for policies limiting such development, we demonstrate that considering firms that sell multiple goods shrinks the set of parameter values for which these policies are necessary (even when the new good is as polluting as the traditional product). If, in addition, the new product exhibits environmental benefits, the social planner is less likely to identify such development as excessive.[5]

[4] Solid-recovered fuels provide an example of a good that, despite being relatively green, is still controversial given that its environmental performance is relatively weak; as recognized by the European Recovered Fuel Organization (EN Report 15359). In particular, these fuels are produced by shredding and dehydrating solid waste consisting of largely combustible components of municipal waste. Another highly cited example is that of oil sands, which require an extremely large amount of water for every gallon of oil produced, and that generate more GHGs emissions than standard oil drilling facilities.

[5] Spence (1975) considers a monopolist's decision to invest in quality, and shows that equilibrium outcomes are not necessarily optimal. While we also demonstrate that the monopolist's decision to develop a green product can be suboptimal, the parameter conditions under which this case arises shrink as brown and green products become more

Firms' private provision of public goods have been studied by Bagnoli and Watts (2003)[6] and Espinola-Arredondo and Zhao (2012), considering that every firm chooses to produce a single product line, e.g., either brown or green. Our paper, however, studies firms' decision to develop additional product lines that are environmentally friendly. Importantly, this characterization reflects the current trends in the green goods industry, whereby firms that traditionally produced polluting goods have also began to offer environmentally friendly products. In a different setting, in which firms sell one type of good and compete a la Bertrand, Andre et al. (2009) show that firms' incentives to develop environmentally friendly products is insufficient, relative to the social optimum, and find that firms are better off with environmental regulation.[7] While we identify a similar result, we also find instances in which the development of green products is socially excessive, and we allow for firms to sell not only their brown product but also a new line of green goods.

The literature on corporate social responsibility (CSR) has extensively analyzed firms' voluntary decision to develop a product that attracts "green" customers, contribute part of their profits to "worthy" causes, etc.; see Baron (2001, 2008) and Besley and Ghatak (2007) for an analysis of CSR.[8] Unlike our paper, these studies consider the green product in isolation, thus abstracting from the potential competition between this good and the polluting good traditionally offered by the same company. Finally, Shaked and Sutton (1982) examine a three-stage game in which firms decide whether to sell a new good and the level of vertical differentiation.[9] Our paper, however, investigates how the level of product differentiation affects firms' decision to develop a line of clean products, which compete against brown goods in the same market, and whether these decisions are socially optimal.

The following section describes the model. Section three analyzes the equilibrium output, and section four examines firms' decision to develop the green product in equilibrium. Section five evaluates the welfare properties of our equilibrium predictions, and section six concludes.

2 Model

Let us assume two firms (1 and 2) which simultaneously produce a homogeneous and polluting good, i.e., brown product, at a symmetric cost $c > 0$. Firm 1 is considering to develop a green product that generates less pollutants, incurring an investment K_1. Upon observing firm 1's development of a new good, firm 2 chooses whether to produce it, incurring an investment K_2, where $K_1, K_2 > 0$

pollutant. Furthermore, our paper considers firms' incentives to develop a new line of green products in addition to the existing brown good that firms traditionally produce, thus giving rise to BSEs that do not exist in Spence's model.

[6] Similar to our paper, they show that firms competing for socially responsible consumers (e.g., consumers with environmental concerns) can lead to an excessive provision of public goods. Arora and Gangopadhyay (1995) consider two firms, each selling a single good and deciding its degree of cleanness and its price.

[7] Their model was extended by Lambertini and Tampieri (2012).

[8] See Dosi and Moretto (2001), Cason and Gangadharan (2002), Mason (2006), Hamilton and Zilberman (2006), Greaker (2006), and Ibanez and Grolleau (2008) for the specific practice of ecolabeling, which is often regarded as CSR.

[9] Their paper has been extended to settings of environmental externalities by Amachera et al. (2004).

are allowed to coincide, $K_1 = K_2$, or differ, $K_1 \neq K_2$.[10] Every firm keeps selling the brown good, whether or not it chose to develop the green good. In addition, given firms' lack of experience producing the green good, their marginal costs of producing it, z, are higher than those of the brown good, i.e., $1 > z > c$.

The production of green goods can affect the demand for brown products when both goods are sufficiently homogeneous. In particular, firm i's inverse demand function for brown and green products are

$$p_i(Q) = 1 - Q - \lambda X \quad \text{and} \quad p_i(X) = 1 - X - \lambda Q,$$

respectively, where $i = \{1, 2\}$ and $Q \equiv q_1 + q_2$ represents the aggregate output of the brown good. Similarly, $X \equiv x_1 + x_2$ denotes the aggregate output of the green product.[11] Parameter $\lambda \in \left[0, \overline{\lambda}\right]$, hence, describes the degree of product differentiation between both goods, where $\overline{\lambda} \equiv \frac{1-z}{1-c}$. Thus, if $\lambda = 0$ products are completely differentiated, and sales of green goods do not affect the demand of brown products, while when $\lambda > 0$ sales of green goods affect the demand for brown goods. Hybrid cars and fossil-fuel cars can be regarded as products that are partially differentiated. For instance, a Toyota Prius exhibits differences with respect to similar cars produced by Toyota, such as the Camry. In particular, while the former is more fuel efficient, the latter has a faster acceleration and more cargo space. As a consequence, consumers prefer one car to the other depending on their preferences for these attributes.[12] In addition, a firm's production decision generates a positive effect on its own profits, arising from selling the new green good, but a negative ("business-stealing") effect, from reducing the sales of the brown good, which only arises when products are not extremely differentiated, i.e., $\lambda \neq 0$.[13] Finally, we do not consider the case in which products are relatively homogeneous, i.e., $\lambda > \overline{\lambda}$, since in that setting no firm would have incentives to develop the green good; a result formally shown in Lemma 1.

3 Equilibrium output

Let us next examine firms' production decision, by separately analyzing the case in which only one, both, or no firm develops the green product.

[10] For completeness, Appendix 1 analyzes the case in which both firms simultaneously and independently decide whether to produce a green good.

[11] This demand specification is, thus, similar to that of Singh and Vives (1984) for the analysis of firms' incentives to compete in either quantities or prices when they produce differentiated products.

[12] More generally, parameter λ captures the product differentiation between the brown and green goods, thus allowing the parameter to embody both the products distinct instrinsic characteristics (e.g., acceleration and cargo space in hybrid and fossil-fuel cars) and their different environmental properties. However, if parameter λ only captures the intrinsic features of the two products, different cases can arise. For instance, when goods are completely differentiated, i.e., $\lambda = 0$, they exhibit totally different intrinsic characteristics, and thus each of them has its own separate market. In this setting, their environmental features can also be completely different (e.g., if the pollution intensity of the green good is zero), similar (if it is the same as that of the brown product), or take intermediate values (if its pollution intensity is smaller).

[13] While the introduction of a green product entails an overall increase in demand, such a development is costly, implying that firm i does not necessarily find profitable to develop the new product, as we describe in the equilibrium results of section 3.

No firm develops the green good. In the case in which no firm produces a green good (NG_1, NG_2), BSE are absent, and every firm i chooses the output level q_i that maximizes its duopoly profits when it produces brown goods (superscript B),

$$\pi_i^B(NG_1, NG_2) \equiv \max_{q_i} \ (1-Q)\, q_i - cq_i. \tag{1}$$

by selecting equilibrium output $q_i^{BB} = \frac{1-c}{3}$, where $i = \{1, 2\}$ and BB denotes that both firms produce the brown good alone.

Both firms develop a green good. If, instead, both firms produce green goods (G_1, G_2), BSE are present, and every firm i maximizes its joint profits from selling both the brown and green product, as follows,

$$\max_{q_i, x_i} \ [(1-Q-\lambda X)\, q_i - cq_i] + [(1-X-\lambda Q)\, x_i - zx_i] \tag{2}$$

by selecting q_i^{GG} and x_i^{GG}, where GG denotes that both firms develop a green good, where

$$q_i^{GG} = \frac{1-c-\lambda(1-z)}{3(1-\lambda^2)} \quad \text{and} \quad x_i^{GG} = \frac{1-z-\lambda(1-c)}{3(1-\lambda^2)}$$

yielding equilibrium profits of

$$\begin{aligned} \pi_i^B(G_1, G_2) &\equiv \left(1 - q_i^{GG} - q_j^{GG} - \lambda(x_i^{GG} + x_j^{GG})\right) q_i^{GG} - cq_i^{GG}, \text{ and} \\ \pi_i^G(G_1, G_2) &\equiv \left(1 - x_i^{GG} - x_j^{GG} - \lambda(q_i^{GG} + q_j^{GG})\right) x_i^{GG} - zx_i^{GG} \end{aligned}$$

when producing the brown (B) and green product (G), respectively.[14]

Only firm i develops a green good. If only firm i produces a green good (G_i, NG_j) and $i \neq j$, it chooses output levels for the green and brown product, q_i^{GB} and x_i^{GB}, that maximize its joint profits

$$\max_{q_i, x_i} \ [(1-Q-\lambda x_i)\, q_i - cq_i] + [(1-x_i-\lambda Q)\, x_i - zx_i]\,. \tag{3}$$

yielding $\pi_i^B(G_i, NG_j) \equiv \left(1 - q_i^{GB} - q_j^{GB} - \lambda x_i^{GB}\right) q_i^{GB} - cq_i^{GB}$ profits from the brown product, and $\pi_i^G(G_i, NG_j) \equiv \left(1 - x_i^{GB} - \lambda(q_i^{GB} + q_j^{GB})\right) x_i^{GB} - zx_i^{GB}$ from the green good. In this setting, firm j only produces the brown product. It, hence, selects the level of q_j^{GB} that solves

$$\max_{q_j} \ (1-Q-\lambda x_i)\, q_j - cq_j \tag{4}$$

entailing $\pi_j^B(G_i, NG_j) \equiv \left(1 - q_i^{GB} - q_j^{GB} - \lambda x_i^{GB}\right) q_j^{GB} - cq_j^{GB}$ profits.

In addition, the leader's commitment to develop green goods alters both firms' best response functions, and thus their posterior Cournot competition, ultimately benefiting the leader. Specifically, if firm i is the only one developing the green product, its best response function for the brown

[14] For compactness, we do not include here the expressions of equilibrium profits in each entry setting. Nevertheless, the proof of Lemma 1 provides them.

good is $q_i(q_j, x_i) = \frac{1-c-2\lambda x_i}{2} - \frac{q_j}{2}$, which experiences a downward shift as its production of the green good, x_i, increases, i.e., $\frac{\partial q_i(q_j,x_i)}{\partial x_i} = -\lambda$. The best response function of its rival (firm j) is $q_j(q_i, x_i) = \frac{1-z-2x_i}{\lambda} - 2q_i$, which also suffers a downward shift as x_i increases, but to a smaller extent than the best response function of firm i does, i.e., $\frac{\partial q_j(q_i,x_i)}{\partial x_i} = -\frac{2}{\lambda}$ where $-\frac{2}{\lambda} < -\lambda$. In particular, each unit of the green good produces a less-than-proportional reduction in the production of firm i's brown good, but a more-than-proportional decrease in the production of firm j's brown good, i.e., $\frac{\partial q_i(q_j,x_i)}{\partial x_i} \in [-1, 0]$ whereas $\frac{\partial q_j(q_i,x_i)}{\partial x_i} \in (-\infty, -2]$ since $\lambda \in [0, 1]$. As a consequence, the profits of the firm developing the green product are larger than those of the firm that does not develop, since

$$\left[\pi_i^B(G_i, NG_j) + \pi_i^G(G_i, NG_j)\right] - \pi_j^B(G_i, NG_j) = \frac{(1 - z - (1 - c)\lambda)^2}{4(1 - \lambda^2)} > 0$$

Hence, the development of green products helps the leader obtain more profits than the follower, i.e., the leader benefits from practicing a "top dog" strategy; as in Fudenberg and Tirole (1984).

Let us next examine how these output levels are affected by a larger homogeneity between the brown and green products, λ, and how these comparative statics ultimately influence firms' incentives to develop the green product.

Lemma 1. *The output difference $q_i - x_i$ is increasing in λ, both when two firms develop the green product and when only one firm develops it. In addition, the profits from the green product are decreasing in λ, and become negative for all $\lambda > \overline{\lambda} \equiv \frac{1-z}{1-c}$.*

Hence, as products become relatively homogeneous, sales of the brown (green) good increase (decrease, respectively). As a consequence, more homogeneous products reduce firms' incentives to develop the green good. Intuitively, the firm that produces green goods faces more competition from brown products, thus reducing its profits. Importantly, we do not consider the case in which products are sufficiently homogeneous, $\lambda > \overline{\lambda}$, since the firm would have no incentives to develop the green good.

Finally, note that when the brown and green product are less differentiated (higher λ), the best response function of the firm developing the green good suffers an inward shift, both in its brown and green product, i.e., $\frac{\partial q_i(q_j,x_i)}{\partial \lambda} = -x_i$ and $\frac{\partial x_i(q_i,q_j)}{\partial \lambda} = -\frac{(2q_i+q_j)}{2}$, respectively. Its rival's best response function $q_j(q_i, x_i)$ also experiences an inward shift, i.e., $\frac{\partial q_j(q_i,x_i)}{\partial \lambda} = \frac{2x_i+z-1}{\lambda^2} < 0$ since $x_i < \frac{1-z}{2}$ for all $\lambda \neq 0$. Therefore, less differentiated products yield a decrease in the sales of the goods produced by all firms. In addition, the profits of the firm developing the green good decrease in λ for all parameter values, since

$$\frac{\partial \left[\pi_i^B(G_i, NG_j) + \pi_i^G(G_i, NG_j)\right]}{\partial \lambda} = \frac{[(1-c)\lambda - (1-z)]\,[1 - c - \lambda(1+z)]}{2(1-\lambda^2)^2}$$

which is negative for all $0 \leq \lambda < \overline{\lambda} \equiv \frac{1-z}{1-c}$. Hence, firms have less incentives to develop the green good as products become less differentiated.

4 Equilibrium results

The following lemma describes the second mover's decision (firm 2) of developing a green good, as a function of firm 1's decision.[15]

Lemma 2. *When firm 1 develops a green good (does not develop), firm 2 responds developing the green product if and only if investment costs satisfy* $K_2 < K^B$ *(*$K_2 < K^A$*, respectively); where* $K^B \equiv \frac{(1-z-(1-c)\lambda)^2}{9(1-\lambda^2)}$ *and* $K^A \equiv \frac{(1-z-(1-c)\lambda)^2}{4(1-\lambda^2)}$ *and* $K^B < K^A$.

Figure 1 depicts cutoffs K^A and K^B for costs $c = \frac{1}{4}$ and $z = \frac{1}{2}$.[16] In region I investment costs are sufficiently small, and firm 2 produces green goods independently of firm 1's decision. In region II investment costs are higher, inducing firm 2 to respond developing green products only after observing that firm 1 does not produce them. Finally, in region III firm 2 does not develop the green product regardless of firm 1's decision, since investment costs are extremely high.

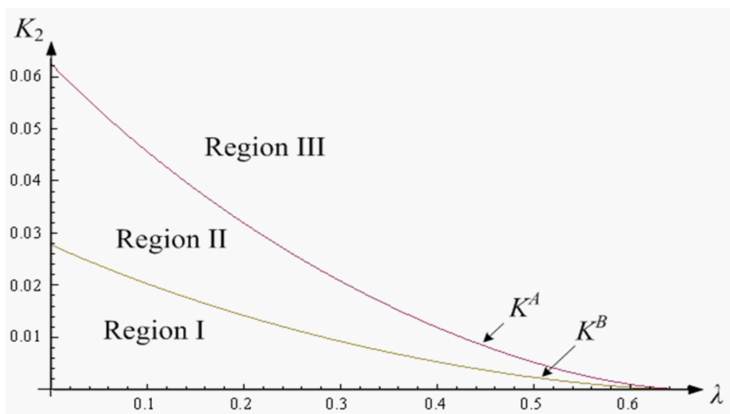

Figure 1. Cutoffs for firm 2's entry decision.

In addition, cutoff K^A satisfies $K^A > K^B$ since green and brown goods are relatively differentiated, i.e., $\lambda \leq \overline{\lambda}$. Intuitively, $K^A > K^B$ reflects that firm 2's net benefits from being the pioneer developing a green product exceed those of being the follower in this industry. Furthermore, cutoffs K^A and K^B are both decreasing in λ, reflecting that, as green and brown products become more homogeneous, the net benefits from entering into the new market decrease, thus shrinking the set of parameter values under which firm 2 enters. Indeed, when products are sufficiently homogeneous ($\lambda \to \overline{\lambda}$), the development of green goods cannot be sustained for any positive investment cost. Such a decreasing pattern holds both when firm 2 is the only producer, as depicted in cutoff K^A,

[15] While Appendix 1 analyzes equilibrium development strategies in the simultaneous version of the game, we focus on its sequential version as most real-life examples of firms adding a line of green products to their existing brown goods did it sequentially. For instance, Toyota was the first automaker to offer hybrid cars, the Prius, along with their other (more polluting) cars, in 1997. Other automakers followed by developing their own hybrid cars afterwards: Honda introduced the Insight in 1999, Mitsubishi the Colt in 2005, and Nissan the Leaf in 2010.

[16] Figure 1 considers $\lambda \leq \overline{\lambda}$, where cutoff $\overline{\lambda}$ becomes $\overline{\lambda} = 2/3$ in this parametric example.

and when both firms develop a green good, as illustrated in K^B.[17]

Anticipating this production pattern from the second mover, the following proposition describes firm 1's equilibrium behavior.[18]

Proposition 1. *In the production of green goods, equilibrium behavior in the unique subgame perfect equilibrium prescribes that:*

1. *Both firms develop a green good,* (G_1, G_2)*, when* $K_1, K_2 < K^B$*;*
2. *Only firm 1 develops a green good,* (G_1, NG_2)*, when* $K_1 < K^A$ *and* $K_2 \geq K^B$*;*
3. *Only firm 2 develops a green good,* (NG_1, G_2)*, when* $K_1 \geq K^A$ *and* $K^A > K_2 \geq K^B$*, and when* $K_1 \geq K^B$ *and* $K_2 < K^B$*; and*
4. *No firm develops a green good,* (NG_1, NG_2)*, when* $K_1, K_2 \geq K^A$*.*

Figures 2a and 2b represent the four equilibrium profiles described in Proposition 1, using the same parameter values as in figure 1. In order to interpret them, note that the first type of equilibrium behavior described in Proposition 1, (G_1, G_2), can be sustained if the investment costs of firm 1 satisfy $K_1 < K^B$, i.e., region (1) in figure 2a, and firm 2's investment costs satisfy $K_2 < K^B$, i.e., also labelled as (1) in figure 2b for firm 2.[19] Intuitively, when the investments costs of firm 1 and 2 are low (high) both of them develop green goods (do not develop), as depicted in area (1) (area 4, respectively). However, when costs are intermediate, only the firm with the lowest investment costs develops a green good, as described in the (G_1, NG_2) and (NG_1, G_2) equilibria, corresponding to areas (2) and (3), respectively.

[17] In addition, note that if products are completely differentiated, $\lambda = 0$, firm 2 develops the green product if $K_2 < \frac{(1-z)^2}{9}$ ($K_2 < \frac{(1-z)^2}{4}$) upon observing that firm 1 developed (did not develop, respectively) the new good. Our equilibrium analysis at the end of this section provides comparative statics of cutoffs K^A and K^B.

[18] If firms instead simultaneously choose to develop the green product, the results in Proposition 1 still apply; except for point (3) which holds under different parameter conditions. For more details on the equilibrium of the simultaneous-move version of the game, see Appendix 1.

[19] A similar representation applies to the second strategy profile, (G_1, NG_2), depicted in areas (2) for firm 1 (in figure 2a) and for firm 2 (in figure 2b).

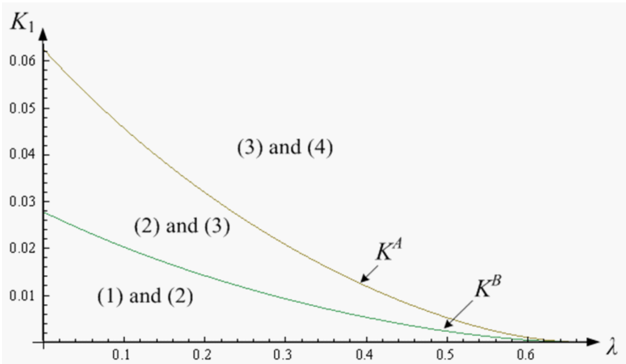

Fig 2a. Equilibrium results: Firm 1.

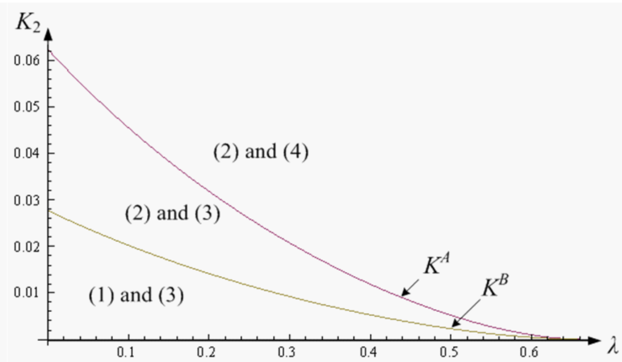

Fig 2b. Equilibrium results: Firm 2.

Hence, even if firms are symmetric (except for their development costs), equilibrium results are not necessarily symmetric. In particular, when the cost of developing the new product is relatively similar for both firms, i.e., $K^A > K_1, K_2 \geq K^B$, our equilibrium predictions only sustain (G_1, NG_2) whereby the first mover takes advantage of his leading position, develops the green product and, as a consequence, deters the follower from the market; a result that goes in line with Schmalensee (1978) and Eaton and Lipsey (1979) whereby product proliferation is used as a tool to prevent entry.[20] Corollary 1 below, which focuses on the special case of perfect symmetry, $K_1 = K_2$, confirms this result.

Corollary 1. *When firms are symmetric in their investment costs, $K_1 = K_2 = K$, a unique equilibrium outcome can be sustained in each region: (G_1, G_2) in region I, (G_1, NG_2) in region II, and (NG_1, NG_2) in region III.*

The three regions identified in Corollary 1 are illustrated in figure 3. Hence, cases (1), (2) and (4) of Proposition 1 can be sustained in the subgame perfect equilibrium, while case (3) cannot. As shown in Proposition 1, if investment costs are asymmetric and the second mover has a substantial cost advantage relative to the leader, i.e., K_2 is sufficiently low, case (3) arises where (NG_1, G_2) and only the follower develops the green good. In contrast, when firms are symmetric in their investment costs, and the leader does not develop a green product, the follower finds unprofitable

[20] In particular, if only firm i had the ability to develop the green good, it would do so when development costs are relatively low, $K < K^B$. However, when firm j also has the ability to develop the green good, firm i might decide to develop under more expensive development costs $K < K^A$, where $K^A > K^B$.

to respond introducing a line of green goods.

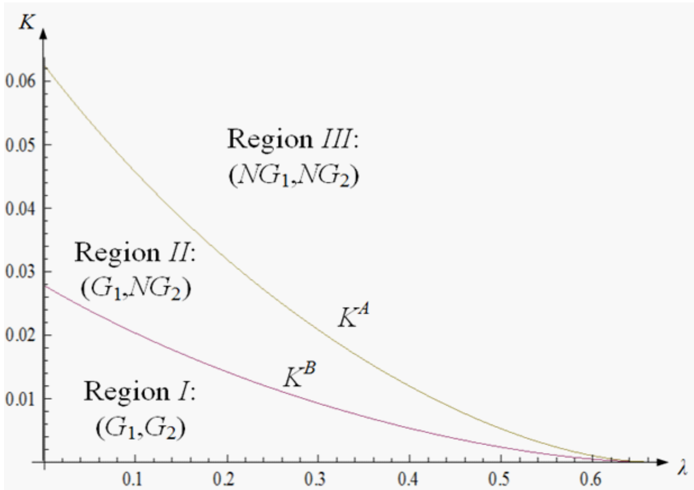

Figure 3. Equilibrium results under symmetry.

Our equilibrium results can help explain the development of a green good by a single firm in the industry when brown and green products are relatively undifferentiated, but the development by several firms when they are highly differentiated. The diaper industry illustrates the first case, as only Huggies offers a green variety (Huggies "Pure & Natural," which uses organic cotton and recyclable materials), while its closest competitor, Pampers, does not. Several customer reviews, such as BabyGearLab.com and Amazon.com, report that Huggies Pure & Natural exhibit similar intrinsic features as traditional diapers, such as their absorption and their ability to prevent leaks. In addition, these reports question its environmental properties, describing them as marginal.[21] Hence, a small differentiation between traditional and green diapers (λ close to $\overline{\lambda}$) could explain why only one firm chose to develop green diapers. In contrast, when products are more differentiated, as in the case of hybrid and fossil-fuel cars, more than one firm may have incentives to develop the green good. In particular, two of the biggest competitors in the U.S. car industry, Ford and GM, developed electric cars, i.e., Ford introduced the Ford Focus Electric car in May 2012 while GM followed with the Chevrolet Spark EV in June 2013. Relative to fossil-fuel cars, these car differ both in their intrinsic features, such as acceleration, cargo space and suspension, and in their environmental properties. Such differentiation (small λ) could justify the decision of both automakers to develop green cars as they would not significantly reduce their sales of traditional fossil-fuel cars.

Comparative statics. Finally, note that both cutoffs experience a downward shift when λ increases. Intuitively, BSE become more severe, thus reducing firms' incentives to develop the green product, which ultimately shrink the regions of investment costs for which at least one firm develops

[21] For more details, see http://www.babygearlab.com/Disposable-Diaper-Reviews/Huggies-Pure-Natural.

the new product. In contrast, when the cost disadvantage between the brown and green product becomes smaller, i.e., z approaches c, both cutoffs K^A and K^B shift upward. In this context, the production of the green good does not entail larger costs than the brown good, thus expanding the region of parameter values for which both firms profitably develop the green product.

For completeness, appendix 1 examines our equilibrium results when firms simultaneously choose whether to develop green products, showing that strategy profiles (1)-(4) in the sequential-move version of the game described in Proposition 1 can also be sustained when firms interact simultaneously. Nonetheless, when both firms' development costs are intermediate, only the leader develops the green good in the sequential-move game, (G_1, NG_2); while an additional equilibrium outcome can also be sustained in the simultaneous version of the game, (NG_1, G_2), where firm 2 becomes the only player developing the green product, thus suggesting a first-mover advantage for firm 1 in the sequential-move game.

5 Welfare comparisons

In this section we evaluate the welfare properties of the above equilibrium predictions where, for simplicity, we examine the case in which firms incur the same development cost, $K_1 = K_2 = K$. At first glance, one could anticipate that the equilibrium where both firms develop the green product entails the largest social welfare. Our following results, however, show that this is not necessarily true under all circumstances.

We consider that the social welfare function includes consumer and producer surplus for brown and green goods, and the environmental damage, which is given by the linear function $d \times (Q + \alpha X)$, where $d \in [0, 1]$, and $\alpha \in [0, 1)$ represents the pollution intensity of the green product relative to the brown product. If the green product is extremely clean, $\alpha = 0$, environmental damage is restricted to the production of the brown good alone, whereas if $\alpha \rightarrow 1$ both products generate similar environmental damages. While the degree of product differentiation of the new green product, λ, and its pollution intensity relative to the brown product, α, could be related, for generality we allow both of them to be independent.[22]

In standard models in which BSE and environmental damages are absent, the development of the new product by an additional firm produces a positive effect on welfare (gain in consumer surplus) and a negative effect (reduction in profits of all existing firms). Considering firms that simultaneously produce brown and green goods introduces an additional negative effect due to the BSE, whereas accounting for the environmental properties of the green good gives rise to a new positive effect on welfare from the reduction in environmental damages. Therefore, whether socially excessive development arises under larger conditions than in standard models critically depends on the relative size of the two welfare effects identified above; as we examine in this section.

[22] For simplicity, our social welfare function abstracts from the cost of raising public funds. Extended models could consider this cost if the regulator provides subsidies to lower firms' development costs (such as fixed R&D and capital investments). However, the introduction of these costs would still yield the presence of an excessive/insufficient number of firms under the same parameter conditions as in our model.

The following proposition analyzes the welfare that arises in our four equilibrium outcomes. (For compactness, cutoffs K_a, K_b and K_c are included in the appendix.)

Proposition 2. *In the development of green products, if* $K_1 = K_2 = K$*:*

1. *The social welfare of outcome* (G_1, G_2) *exceeds that of* (G_1, NG_2) *if and only if* $K < K_a$*;*
2. *The social welfare of outcome* (G_1, NG_2) *is larger than that of* (NG_1, NG_2) *if and only if* $K < K_b$*; and*
3. *The social welfare of outcome* (G_1, G_2) *exceeds that of* (NG_1, NG_2) *if and only if* $K < K_c$*,*

where $K = K_a$ *solves* $SW_{G_1G_2} = SW_{G_1NG_2}$*,* $K = K_b$ *solves* $SW_{G_1NG_2} = SW_{NG_1NG_2}$*, and finally,* $K = K_c$ *solves* $SW_{G_1G_2} = SW_{NG_1NG_2}$*.*

In the following subsections, we separately explore the role of the different parameters that differentiate our analysis with that in standard models of product proliferation. In this spirit, we first examine the three cutoffs of Proposition 2 in the case in which environmental damages are absent, i.e., $d = 0$, and thus all welfare effects originate from consumer and producer surplus alone. We afterwards introduce environmental damages, $d > 0$, but abstract from the pollution intensity of the green good, i.e., $\alpha = 0$, which helps us disentangle the effect of pollution on welfare when it only stems from the brown product, i.e., the green good is completely clean. Finally, and within the context of positive environmental damages, we examine the role of pollution intensity of the green good, thus considering $\alpha > 0$, and the extreme case in which both products yield similar environmental damages.

5.1 No environmental damages

Figure 4 depicts cutoffs K_a, K_b and K_c for the case in which environmental damages are absent, $d = 0$, thus identifying, for each $(K, \lambda)-$pair, the number of firms that should develop the green product from a socially optimal perspective.[23] In particular, when development costs are sufficiently low, $K < \min\{K_a, K_c\}$, the regulator would prefer the (G_1, G_2) outcome (unshaded area); when costs satisfy $K > \max\{K_b, K_c\}$ outcome (NG_1, NG_2) becomes optimal (left section of the shaded area); while if development costs are intermediate, $\min\{K_a, K_c\} < K < \max\{K_b, K_c\}$ outcome (G_1, NG_2) is socially desirable (right section of the shaded area).[24]

[23] Following our numerical example in previous sections of the paper, figure 4 considers costs $c = 1/4$ and $z = 1/2$. Other parameter values yield similar qualitative results and can be provided by the authors upon request.

[24] For this numerical example, outcome (G_1, NG_2) arises under condition $\min\{K_a, K_c\} < K < \max\{K_b, K_c\}$, which in this case implies that K satisfies $K_c < K < K_b$; as depicted in the right-hand side of figure 4.

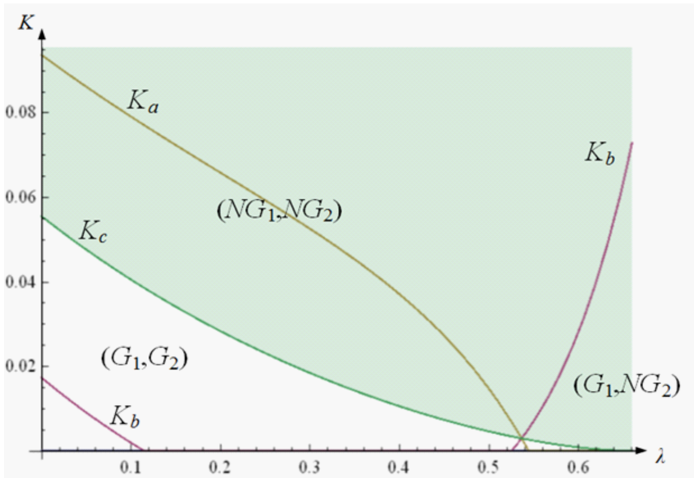

Fig 4. Socially optimal outcomes when $d = 0$.

Figure 5 superimposes the socially optimal outcomes of figure 4 on top of the equilibrium outcomes described in figure 3, where shaded areas indicate the set of $(K, \lambda)-$pairs for which the equilibrium arising in that region is socially optimal. More precisely, the shaded areas identify parameter combinations under which the number of firms developing the product in the unregulated equilibrium coincides with the number of firms that a social planner would select in order to maximize social welfare.[25]

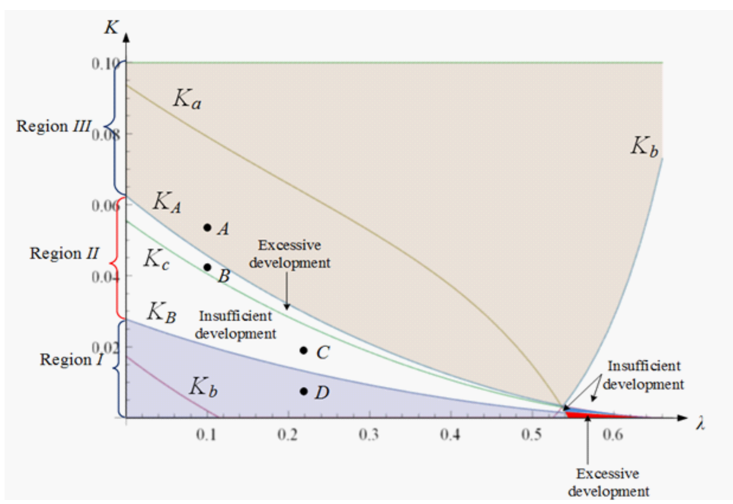

Fig 5. Insufficient and excessive development when $d = 0$.

[25] While the shaded areas describe optimality in terms of the number of firms developing the green good, the externality that both types of products generate is still not addressed by any policy tool (such as taxes or quotas), ultimately implying that these areas only identify second-best optima. (Nevertheless, and for compactness, we refer to shaded regions as optima.)

Let us sequentially focus on different areas of figure 5. First, in the unshaded region depicting an insufficient development of green products (right-hand side of the figure), BSEs are sufficiently large to deter both firms from developing the green product, i.e., outcome (NG_1, NG_2) arises. However, the relatively undifferentiated product yields a large increase in consumer surplus which, unlike firms in their decision to develop, the regulator takes into account. Hence, in this region the regulator favors outcome (G_1, NG_2), as depicted in figure 5, ultimately leading to an insufficient development of green products.

Moving leftward, when the products become more differentiated (lower λ), firms face a smaller BSE, thus potentially attracting one or both of them to develop the green product (as depicted in regions I and II, respectively). In this context, the number of firms arising in equilibrium can coincide with that selected by the social planner. In particular, as products become more differentiated, the development of new products entails the presence of two relatively independent duopolies: one selling brown and the other green products, each of them generating inefficiencies. (Recall that, since in this setting we consider no environmental damages, these inefficiencies arise from two mostly independent duopolies rather than from pollution.) Hence, the welfare loss from these inefficiencies offset development costs only when the latter are sufficiently small. Thus, not only both firms would develop the green product in equilibrium, but the regulator would also find the presence of both firms as socially optimal. Point d in figure 5 illustrates this scenario. The opposite argument applies when development costs are sufficiently high to lead both firms and regulator to support outcome (NG_1, NG_2) in which no firm develops the green product, as depicted in point a. In contrast, when costs are intermediate, the number of firms developing the green good in equilibrium becomes either socially excessive or insufficient. Specifically, it is excessive when development costs are sufficiently high to lead the regulator to favor no green firm whatsoever, (NG_1, NG_2), yet low enough to attract one firm to the green industry in equilibrium, (G_1, NG_2). This case is illustrated in point b of the figure. Finally, development is socially insufficient when costs are relatively low to induce outcome (G_1, G_2) as socially optimal, yet high enough for only one firm to voluntarily develop the green good in equilibrium, i.e., (G_1, NG_2); as depicted in point c.

As discussed in section 3, less differentiated products (higher λ) produce an inward shift in the best response function of all firms, both for its brown and green products, ultimately reducing the aggregate output of both types of goods. Profits thus decrease as products become less differentiated and aggregate sales shrink. Less differentiated goods, however, give rise to two effects on consumer surplus: a positive effect, as firms are forced to charge lower prices for their more homogeneous products; and a negative effect, as larger values of λ reduce the demand for both products, thus decreasing sales. While the negative effect dominates, i.e., $\frac{\partial[CS(Q)+CS(X)]}{\partial\lambda} = \frac{c+z-2}{3(1+\lambda)^2} < 0$ given that $1 > z > c$ by assumption, it diminishes as products become less differentiated (larger values of λ). Importantly, this result does not imply that the development of green goods decreases consumer surplus, but instead that, once these goods are offered, less differentiation reduces sales more significantly than prices, ultimately decreasing consumer surplus.

5.2 Introducing environmental damage

Let us next examine the role of environmental damage in the previous results. Figure 6 depicts cutoffs K_a, K_b and K_c for the case in which $d = 1/2$, and also includes firms' cutoffs K^A and K^B. For simplicity, we consider a pollution intensity of $\alpha = 0$, assumption that is relaxed in the next subsection. While the cutoffs determining under which conditions firms choose to develop the green product, K^A and K^B, are unaffected by parameter d, the welfare cutoffs from Proposition 2 shift, producing an expansion of the region under which equilibrium outcomes entail an insufficient development of green products, and a shrink of the region for which such development is socially excessive (in our simulation, this area almost disappears). Intuitively, the welfare loss from pollution now leads to one or two green plants being optimal under larger parameter conditions. Nevertheless, even in the case of a perfectly clean green product, $\alpha = 0$, the regulator still might find situations in which the development of this good is socially excessive. As depicted in the figure, when the green product is relatively undifferentiated to the brown good (high λ), the regulator would only consider optimal the presence of one firm in the green industry, while the low development costs attract both firms; thus yielding a socially excessive number of firms.

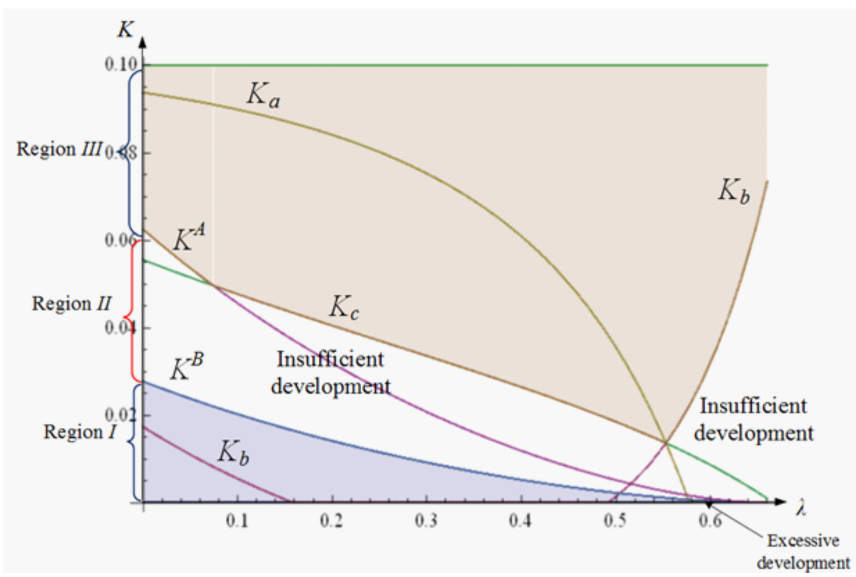

Fig 6. Insufficient and excessive development when $d = 1/2$.

5.3 Introducing pollution intensity

In order to sequentially add further dimensions to our analysis, the previous discussion considered a completely green product, i.e., $\alpha = 0$. Let us next examine the role of pollution intensity, α, in our results, as depicted in Figure 7 where $\alpha = 0.8$.[26] The region for which the equilibrium number

[26] In particular, cutoffs K_a and K_c lie on the negative quadrant. Thus, for all $K > K_b$ the outcome (NG_1, NG_2) is socially optimal, which only coincides with the equilibrium outcome in region III (in region I and II one or both

of firms is socially excessive expands as the pollution intensity of the green product increases and becomes almost as pollutant as the brown good. Intuitively, this setting describes the development of a new product that does not provide significant green properties, and thus the regulator finds the equilibrium number of firms in this industry excessive in several contexts.

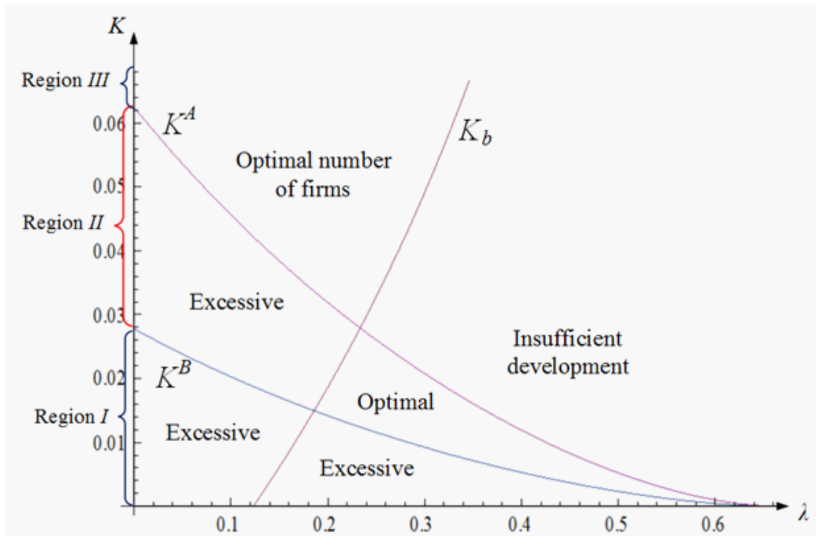

Fig 7. Insufficient and excessive development when $\alpha = 0.8$.

A natural question is whether social welfare in equilibrium is concave or convex in the number of firms developing the green product. In our setting, concavity would imply that the welefare increase from having only one firm developing the green good, $SW_{G_1NG_2} - SW_{NG_1NG_2}$, is larger than that from having both firms develop it, $SW_{G_1G_2} - SW_{G_1NG_2}$. Our results show that welfare is not necessarily concave in the number of firms developing the green good. In particular, concavity arises for low values of λ but convexity emerges otherwise; a result that holds both when environmental damages are present and absent, and both with and without pollution intensity. Intuitively, when products are highly differentiated, the development of green products by the first firm yields a larger welfare increase than that brought by the second firm. In contrast, when goods are relatively homogeneous, the development by the second firm brings a larger welfare increase than that of the first firm developing the green good. (For more details on the social welfare differences, see Appendix 3.)

5.4 Policy recommendations

From a policy perspective, our results suggest that the regulator could strategically vary the administrative costs of developing the green product in order to promote the emergence of combinations of (K, λ) that yield the equilibrium with the largest social welfare. In particular, he could modify

firms develop the green good). For all $K \leq K_b$, outcome (G_1, NG_2) is optimal, thus coinciding with the equilibrium outcome in region II alone.

the value of K by altering the amount of paperwork required for opening a new plant that produces the green good, the timing of the permits, etc. (Our welfare comparisons also hold when environmental damage is convex in output; as examined in Appendix 2.)

Low pollution intensity. Let us first consider a setting in which only the brown good generates pollution, i.e., $\alpha = 0$. Figure 8 reproduces Figure 6 (where pollution was confined to the brown product alone, i.e., $d = 1/2$ and $\alpha = 0$), and Table I evaluates the social welfare arising under the parameter combinations considered in points $A - F$ of Figure 8. As the table indicates, when $\lambda = 0.1$, the reduction in administrative costs, illustrated in the downward movement from point B to C, entails a welfare improvement. Specifically, since the green product is completely clean in this context, the development of green goods by both firms in C yields a larger social welfare than when only one firm develops it (in point B). However, moving upwards from B to A is actually welfare reducing, since in A no firm develops a product that is particularly clean.[27]

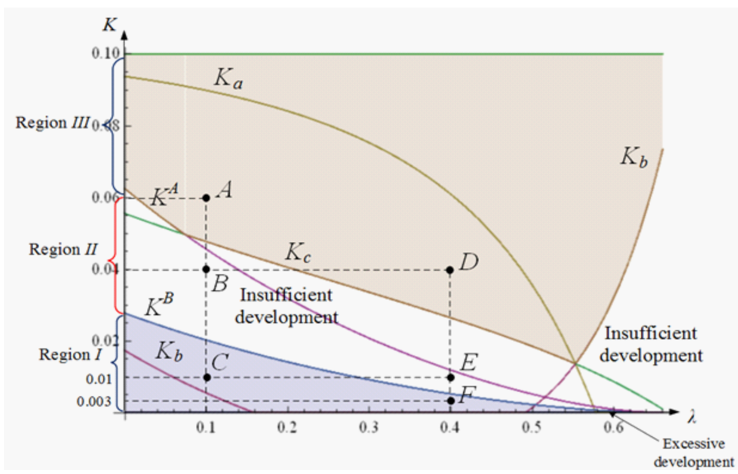

Figure 8. Low pollution intensity, $\alpha = 0$.

	K	λ	$Welfare$
A	0.06	0.1	0
B	0.04	0.1	0.049
C	0.01	0.1	0.075
D	0.04	0.4	0
E	0.01	0.4	0.051
F	0.003	0.4	0.046

Table I. Welfare comparisons: Low pollution intensity, $\alpha = 0$.

When products become more homogeneous, $\lambda = 0.4$ (as in points $D - F$, on right-hand side of

[27] For the parameter values in Table I, where $d = 1/2$, the welfare benefit from consumer and producer surplus is exactly offset by the environmental damage from the brown product, thus yielding a zero welfare level. Other numerical simulations with $d < 1/2$ yield positive welfare levels, and can be provided by the authors upon request.

figure 8), the BSE is large, thus yielding two welfare effects. On one hand, aggregate profits when two firms develop the green good are lower than those of a single monopolist in the green market.[28] On the other hand, BSEs also induce a large reduction in the production of the brown good, which entails a lower pollution. The profit loss, however, offsets the second effect, ultimately implying that the social welfare when only one firm develops the green good (point E) is larger than when both firms do (point F). In addition, the development of the green product by at least one firm (as in points E and F) yields a higher social welfare than having no firm developing it (as in point D). Intuitively, the regulator has incentives to attract one or both firms to the green industry given the significant environmental properties of the green good.

Summarizing, our findings indicate that, even when the green product is extremely clean (it produces no environmental damages) the regulator would not necessarily have incentives to promote two firms in the green industry. Indeed, the regulator would not support the presence of two firms if the new product, despite being completely clean, is relatively undifferentiated with respect to the brown good (high λ). He would nonetheless favor the presence of two firms if the green product is highly differentiated.

High pollution intensity. Let us now examine the welfare properties of policies varying development costs when the green product is not particularly clean. Figure 9 reproduces Figure 7 (where $d = 1/2$ and $\alpha = 0.8$) and Table II describes the social welfare that arises in points $A - G$ of the figure. Intuitively, when the green product becomes more damaging, social welfare is higher when no firm develops the green good than when one or both do.[29] When the green product is relatively pollutant, while BSEs can still reduce the production of brown product, the increase in overall pollution is now sufficiently large to yield an unambiguous welfare loss if one or more firms develop the green good. Importantly, this result holds even when BSEs are large, i.e., for all values of λ. Our results, hence, suggest that the regulator should not facilitate the development of green products when, despite being cleaner than the brown good, their environmental properties

[28] Note that this is not necessarily the case when goods are relatively differentiated.

[29] Graphically, when $\lambda = 0.1$ (in the left-hand side of figure 9), moving from point A to either B or C entails a welfare reduction. Similarly, when $\lambda = 0.3$ (in the right-hand side of figure 9), moving from D to either E, F or G yields a welfare loss.

are relatively poor (high pollution intensity, α).

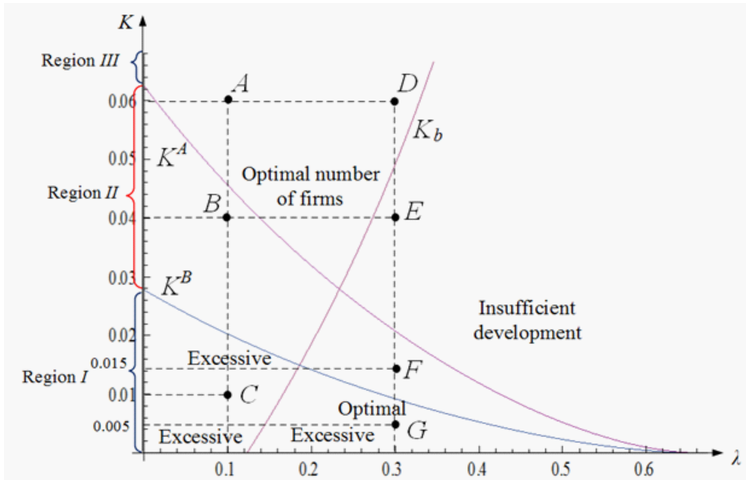

Figure 9. High pollution intensity, $\alpha = 0.8$.

	K	λ	$Welfare$
A	0.06	0.1	0
B	0.04	0.1	−0.056
C	0.01	0.1	−0.039
D	0.06	0.3	0
E	0.04	0.3	0
F	0.015	0.3	−0.066
G	0.005	0.3	−0.023

Table II. Welfare comparisons: High pollution intensity, $\alpha = 0.8$.

6 Conclusions

This paper examines firms' incentives to develop green goods, which compete with the brown product that the firm traditionally sells. We identify strategy profiles in which both, one or no firm develop the product. However, we demonstrate that both firms' developing the new product is not necessarily socially efficient, i.e., we predict an excessive production of green goods under certain conditions. Our results also provide policy recommendations that help regulatory authorities modify administrative costs in order to promote equilibrium outcomes that generate the highest social welfare. In particular, while regulators have incentives to reduce these administrative costs when the green product is extremely clean and sufficiently differentiated, they might prefer to increase them to an intermediate level when the green good, despite being extremely clean, is relatively undifferentiated. Finally, when the green product does not exhibit strong environmental properties, our findings indicate that regulatory authorities should essentially hinder the development of green products in order to ultimately avoid firms from operating in this industry.

Our paper assumes that firms are perfectly informed about their rival's cost structure. In several industries, however, firms are unable to observe each other's costs. Hence, the development of green goods by every firm could convey information about their competitiveness to potential entrants in this new industry. The incentives to deter competitors could, hence, induce the leader to develop the green product under larger conditions than under a complete information setting, thus emphasizing the excessive production of green goods identified in this paper. Other venues of further research might include asymmetric production costs between firm 1 and 2, i.e., the second-mover's costs could be lower if it learned from the product developed by firm 1; allow for the degree of product differentiation to be endogenously determined by each firm; or examine the role of standard environmental policies, such as emission fees and subsidies, in inducing socially optimal outcomes.

7 Appendices

7.1 Appendix 1 - Simultaneous-move game

Proposition A. *In the production of green goods, Nash equilibrium behavior in the simultaneous-move game is:*

1. *Both firms develop a green good,* (G_1, G_2)*, when* $K_1, K_2 < K^B$*;*
2. *Only firm 1 develops a green good,* (G_1, NG_2)*, when* $K_1 < K^A$ *and* $K_2 \geq K^B$*;*
3. *Only firm 2 develops a green good,* (NG_1, G_2)*, when* $K_1 \geq K^B$ *and* $K_2 < K^A$*; and*
4. *No firm develops a green good,* (NG_1, NG_2)*, when* $K_1, K_2 \geq K^A$*.*

Hence, strategy profiles (1), (2) and (4) can be supported under the same parameter conditions when firms interact simultaneously and sequentially. However, (NG_1, G_2) in which only firm 2 develops green products can be sustained under more general conditions when this firm simultaneously chooses whether to develop the green good than when it acts as the follower upon observing the leader's decision. In particular, when both firms' development costs are intermediate, i.e., $K^A > K_1, K_2 \geq K^B$, the sequential-move game prescribes that a unique equilibrium emerges in which firm 1 develops the green good, (G_1, NG_2), while under the simultaneous version of the game, two possible outcomes arise, (G_1, NG_2) and (NG_1, G_2) in which either firm 1 or 2 develop in equilibrium, thus reflecting that firm 1 benefits from its first-mover advantage.

Proof. As described in Lemma 2, the best response function for any firm $i = \{1, 2\}$ prescribes that, if the rival firm j develops the green product, firm i responds developing it if and only if $K_i < K^B$. However, if the rival firm does not develop, firm i responds developing the green good if and only if $K_i < K^A$. Let us now examine equilibrium behavior in the nine possible parameter combinations that emerge from this best response functions.

Case 1 (Firm 1's costs are in region I). *Case 1a.* When firm 2's costs are in region I, developing the green product is a strictly dominant strategy for both firms, and thus (G_1, G_2) is the unique Nash equilibrium outcome.

Case 1b. When firm 2's costs are in region II, developing the green product is a strictly dominant strategy only for firm 1, and thus firm 2 responds not developing this good. Hence, (G_1, NG_2) arises.

Case 1c. If firm 2's costs are in region III, developing (not developing) the green product is a strictly dominant strategy for firm 1 (firm 2, respectively). Therefore, (G_1, NG_2) also arises in this case.

Case 2 (Firm 1's costs are in region II). *Case 2a.* When firm 2's costs are in region I, developing the green product is a strictly dominant strategy only for firm 2, and thus (NG_1, G_2) is the unique Nash equilibrium outcome.

Case 2b. When firm 2's costs are in region II, two equilibria arise: (G_1, NG_2) and (NG_1, G_2). In these equilibria, neither firm has incentives to deviate: on one hand, the firm which did not develop the green product cannot increase its profits by developing it, since its rival already developed the good; on the other hand, the firm that developed the product would reduce its profits by deviating towards not developing the product, since it is currently the only producer in the green market.

Case 2c. If firm 2's costs are in region III, not developing is a strictly dominant strategy for firm 2. Hence, (G_1, NG_2) arises in this case.

Case 3 (Firm 1's costs are in region III). *Case 3a.* When firm 2's costs are in region I, developing (not developing) the green product is a strictly dominant strategy for firm 2 (firm 1, respectively). Therefore, (NG_1, G_2) is the unique Nash equilibrium outcome.

Case 3b. When firm 2's costs are in region II, not developing the green product is still a strictly dominant strategy for firm 1, and firm 2 responds developing the green good, i.e., (NG_1, G_2).

Case 3c. If firm 2's costs are in region III, not developing the green product is a strictly dominant strategy for both firms, and (NG_1, NG_2) arises.

Summarizing, the symmetric equilibrium outcomes (G_1, G_2) can only be supported when $K_1, K_2 < K^B$, and (NG_1, NG_2) can be sustained when $K_1, K_2 \geq K^A$. However, equilibrium outcome (G_1, NG_2) can be supported under four different settings: i) $K_1 < K^B$ and $K^A > K_2 \geq K^B$; ii) $K_1 < K^B$ and $K_2 \geq K^A$; iii) $K^A > K_1, K_2 \geq K^B$; and iv) $K^A > K_1 \geq K^B$ and $K_2 \geq K^A$. Hence, cases (i) and (ii) can be collapsed into $K_1 < K^B$ and $K_2 \geq K^B$, while cases (iii) and (iv) can be expressed as $K^A > K_1 \geq K^B$ and $K_2 \geq K^B$. Finally, these two conditions can be summarized as $K_1 < K^A$ and $K_2 \geq K^B$. Similarly, equilibrium outcome (NG_1, G_2) can be sustained under four different parameter conditions: a) $K^A > K_1 \geq K^B$ and $K_2 < K^B$; b) $K^A > K_1, K_2 \geq K^B$; c) $K_1 \geq K^A$ and $K_2 < K^B$; and d) $K_1 \geq K^A$ and $K^A > K_2 \geq K^B$. Therefore, cases (a) and (b) can be collapsed into $K^A > K_1 \geq K^B$ and $K_2 < K^A$, whereas cases (c) and (d) can be expressed as $K_1 \geq K^A$ and $K_2 < K^A$. Finally, these two conditions can be summarized as $K_1 \geq K^B$ and $K_2 < K^A$. ■

7.2 Appendix 2 - Convex environmental damage

When the environmental damage is convex in output, i.e., $ED = d(Q + \alpha X)^2$, the welfare comparisons of section 5.4 still hold. The following two figures evaluate the welfare arising in each of the three equilibrium outcomes for similar parameter values as in figures 8 and 9, i.e., $d = 1/2$. Similarly as in section 5.4, when the green product is completely clean, $\alpha = 0$, social welfare is the highest when both firms develop the green product when goods are relatively differentiated, $\lambda = 0.1$, as depicted in point C; but becomes the highest when only one firm develops the green product if goods are more homogeneous, $\lambda = 0.4$, as illustrated in point E. However, when the green product exhibits a poor environmental performance, $\alpha = 0.8$, social welfare is the highest when no firm develops the green good, both when products are differentiated (as depicted at point A in the case that $\lambda = 0.1$) and when they are undifferentiated (as illustrated by point D in the case that $\lambda = 0.3$).

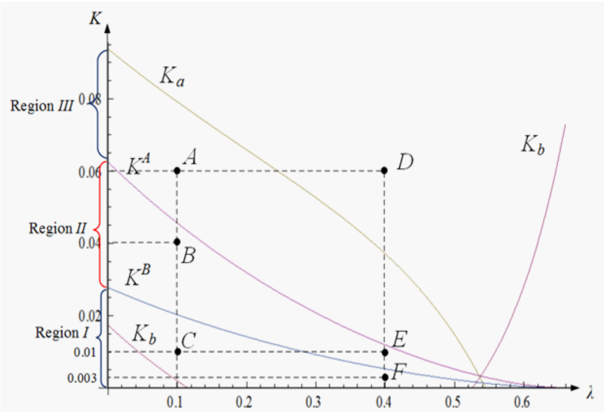

Figure A1. Low pollution intensity, $\alpha = 0$.

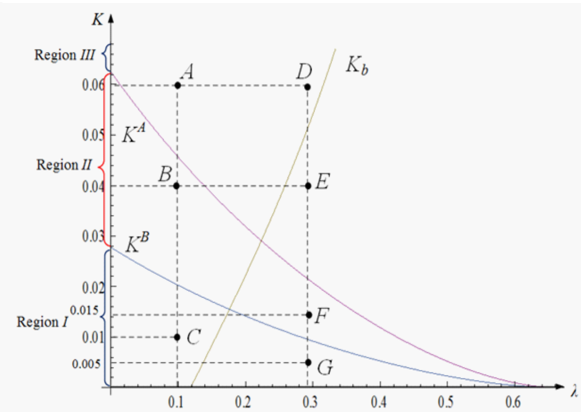

Figure A2. High pollution intensity, $\alpha = 0.8$.

	K	λ	$Welfare$
A	0.06	0.1	0.125
B	0.04	0.1	0.174
C	0.01	0.1	0.199
D	0.04	0.4	0.125
E	0.01	0.4	0.174
F	0.003	0.4	0.169

	K	λ	$Welfare$
A	0.06	0.1	0.125
B	0.04	0.1	0.051
C	0.01	0.1	0.065
D	0.06	0.3	0.125
E	0.04	0.3	0.125
F	0.015	0.3	0.037
G	0.005	0.3	0.096

Table AI. Welfare comparisons: Low pollution intensity (left) and high pollution intensity (right).

7.3 *Appendix 3 - Welfare gains*

The difference in welfare gains $(SW_{G_1NG_2} - SW_{NG_1NG_2}) - (SW_{G_1G_2} - SW_{G_1NG_2})$ is

$$\frac{1}{36(1-\lambda^2)^2}(11 - 18\alpha d - 4\lambda + 32d\lambda - 15\lambda^2 - 50d\lambda^2 + 4\lambda^3 + 4d\lambda^3 - 5\lambda^4 + 14d\lambda^4 +$$
$$c^2(4(3+4d)\lambda^3 - 36 - 18\alpha d(-2+\lambda)^2 - 12\lambda + (11-16d)\lambda^2 + (14d-11)\lambda^4) - 4z$$
$$-20\lambda z - 48d\lambda z + 4\lambda^2 z + 36d\lambda^2 z + 2\lambda^3 z + 12d\lambda^3 z - 16z^2 + 16d\lambda z^2 + 7\lambda^2 z^2 - 2d\lambda^2 z^2 -$$
$$2c(18 + 18\alpha d(\lambda-2) + 2(7d-4)\lambda^4 - 36z + \lambda(8z + 8d(1-z) - 35)$$
$$+2\lambda^2(9z - 5 + 8d(z-2)) + \lambda^3(17 - 8z + 2d(5+3z))))$$

7.4 *Proof of Lemma 1*

No firm develops a green good. When no firm produces green goods, every firm i's production level of brown goods under duopoly is $q_i^{BB} = \frac{1-c}{3}$, for all $i = \{1, 2\}$, entailing equilibrium profits of $\pi_i^B(NG_1, NG_2) = \frac{(1-c)^2}{9}$.

Only firm i develops a green good. In this case, firm i and j's profit maximizing output of brown goods are

$$q_i^{GB} = \frac{[2 + (\lambda - 3)\lambda + 3\lambda z] - \left(2 + \lambda^2\right) c}{6(1 - \lambda^2)} \quad \text{and} \quad q_j^{GB} = \frac{1 - c}{3}$$

while firm i's production of green good is

$$x_i^{GB} = \frac{1 - c - (1 - \lambda)c}{2(1 - \lambda^2)},$$

since best response functions are given by $q_i\left(q_j, x_i\right) = \frac{1-c-2\lambda x_i}{2} - \frac{q_j}{2}$, $q_j\left(q_i, x_i\right) = \frac{1-z-2x_i}{\lambda} - 2q_i$, and $x_i\left(q_i, q_j\right) = \frac{1-z-\lambda(2q_i+q_j)}{2}$, respectively. Hence, firm i's equilibrium profits from the brown good are

$$\pi_i^B(G_i, NG_j) = \frac{[1 - c]\left[(\lambda - 2)(\lambda - 1) + 3\lambda z - (2 + \lambda^2)c\right]}{18(1 - \lambda^2)},$$

firm i's profits from the green product are

$$\pi_1^G(G_i, NG_j) = \frac{[1 - z - (1 - c)\lambda]\,[3 - \lambda - 3z + \lambda c]}{12(1 - \lambda^2)},$$

which is positive for all $\lambda \leq \frac{1-z}{1-c} \equiv \overline{\lambda}$, and firm j's profits are $\pi_j^B(G_i, NG_j) = \frac{(1-c)^2}{9}$. (The equilibrium profits in which only firm j invests are analogous.) The output difference $q_i^{GB} - x_i^{GB}$ is positive and increasing in λ since

$$\frac{\partial\left(q_i^{GB} - x_i^{GB}\right)}{\partial\lambda} = \frac{z - c}{2(1 - \lambda)^2}$$

is positive given that $z > c$.

Both firms develop a green good. In this case, firm i's profit maximizing outputs from producing brown and green goods are, respectively,

$$q_i^{GG} = \frac{1 - c - \lambda(1 - z)}{3(1 - \lambda^2)} \quad \text{and} \quad x_i^{GG} = \frac{1 - z - \lambda(1 - c)}{3(1 - \lambda^2)}$$

entailing equilibrium profits of

$$\pi_i^B(G_i, G_j) = \frac{1 - c}{3} q_i^{GG} = \frac{[1 - c]\,[1 - c - (1 - \lambda)c]}{9(1 - \lambda^2)},$$

when producing brown goods, and

$$\pi_i^G(G_i, G_j) = \frac{1-z}{3} q_i^{GG} = \frac{(1-z)\left[1-z-(1-\lambda)c\right]}{9(1-\lambda^2)}$$

when producing green goods. The output difference $q_i^{GG} - x_i^{GG}$ is positive and increasing in λ since

$$\frac{\partial\left(q_i^{GG} - x_i^{GG}\right)}{\partial \lambda} = \frac{z-c}{3(1-\lambda)}$$

is positive given that $z > c$. ■

7.5 *Proof of Lemma 2*

Let us analyze the production decision of the second mover (firm 2). If firm 1 does not develop green goods, then firm 2 responds producing them if its profits from brown goods and its profits from green goods (net of investment costs) exceed those from staying out,

$$\pi_2^B(NG_1, G_2) + \pi_2^G(NG_1, G_2) - K_2 > \pi_2^B(NG_1, NG_2). \tag{C_2^A}$$

Note that the difference $EGB_2(NG_1) \equiv \pi_2^B(NG_1, G_2) - \pi_2^B(NG_1, NG_2)$ captures the effect that the development of green goods produces on sales of the brown good (EGB). Hence, condition (C_2^A) can be compactly expressed as

$$\pi_2^G(NG_1, G_2) + EGB_2(NG_1) \equiv K^A > K_2$$

where, in particular, cutoff $K^A = \frac{(1-z-(1-c)\lambda)^2}{4(1-\lambda^2)}$. Note that when products are completely differentiated, $\lambda = 0$, this cutoff coincides with the profits that firm 2 obtains from the green product, i.e., $K^A = \frac{(1-z)^2}{4}$.

If, instead, firm 1 enters, firm 2 responds producing green goods as well if

$$\pi_2^B(G_1, G_2) + \pi_2^G(G_1, G_2) - K_2 > \pi_2^B(G_1, NG_2), \tag{C_2^B}$$

which can similarly be expressed as $\pi_2^G(G_1, G_2) + EGB_2(G_1) \equiv K^B > K_2$, where $EGB_2(G_1) \equiv \pi_2^B(G_1, G_2) - \pi_2^B(G_1, NG_2)$. Cutoff $K^B = \frac{(1-z-(1-c)\lambda)^2}{9(1-\lambda^2)}$ and, when $\lambda = 0$, it coincides with the profits that firm 2 obtains from the green product, i.e., $K^B = \frac{(1-z)^2}{9}$. ■

7.6 *Proof of Proposition 1*

In the case that firm 2 responds producing green goods regardless of firm 1's action, i.e., region I of figure 1, i.e., $K_2 < K^B$, firm 1 develops green goods if

$$\pi_1^B(G_1, G_2) + \pi_1^G(G_1, G_2) - K_1 > \pi_1^B(NG_1, G_2), \tag{C_1^A}$$

or $K^B > K_1$. Therefore, if $K^B > K_1$ both firms produce green goods, (G_1, G_2). However, if $K^B \leq K_1$ only firm 2 produces green goods, (NG_1, G_2), since its investments costs are low while those of firm 1 are relatively high.

If firm 2 responds developing green goods only after observing that firm 1 does not produce them, i.e., region II, i.e., $K^A > K_2 \geq K^B$, firm 1 chooses to develop green goods if

$$\pi_1^B(G_1, NG_2) + \pi_1^G(G_1, NG_2) - K_1 > \pi_1^B(NG_1, G_2), \qquad (C_1^B)$$

or $K^A > K_1$. Hence, when $K^A > K_1$ the subgame perfect equilibrium (SPNE) predicts that firm 1's production decision deters firm 2 from producing green goods, (G_1, NG_2), since firm 1's investment costs are relatively low, while its opponent's are high. In contrast, when $K^A \leq K_1$ the opposite strategy profile can be sustained, in which firm 1 does not produce them and, hence, firm 2 responds developing green goods, i.e., (NG_1, G_2).

Finally, if firm 2 responds not producing green goods regardless of firm 1's production decision, region III, i.e., $K_2 \geq K^A$, firm 1 chooses to produce green goods if

$$\pi_1^B(G_1, NG_2) + \pi_1^G(G_1, NG_2) - K_1 > \pi_1^B(NG_1, NG_2), \qquad (C_1^C)$$

or $K^A > K_1$. Hence, when $K^A > K_1$ the SPNE predicts that only firm 1 produces green goods, (G_1, NG_2); whereas when $K^A \leq K_1$ no firm develops green products, i.e., (NG_1, NG_2). Finally, note that the case in which condition C_2^B holds but C_2^A does not, cannot be sustained since $\lambda < \overline{\lambda}$, which implies that cutoff K^A lies above K^B. Therefore, equilibrium (G_1, NG_2) can be sustained when $K_1 < K^A$ and $K_2 \geq K^A$, and when $K_1 < K^A$ and $K^A > K_2 \geq K^B$. We can, hence, collapse both cases as $K_1 < K^A$ and $K_2 \geq K^B$. ■

7.7 *Proof of Proposition 2*

Both firms develop a green good. The social welfare when both firms produce green goods, $SW_{G_1 G_2}$, is defined as

$$\begin{aligned} SW_{G_1G_2} &= CS(Q) + CS(X) + \pi_1^B(G_1, G_2) + \pi_1^G(G_1, G_2) - K_1 \\ &\quad + \pi_2^B(G_1, G_2) + \pi_2^G(G_1, G_2) - K_2 - d\left(Q^2 + \alpha X^2\right). \end{aligned}$$

where $CS(Q) = \frac{2(1-c)(c+\lambda(1-z)-1)}{9(\lambda^2-1)}$, $CS(X) = \frac{2(1-z)[(1-c)\lambda+z-1]}{9(\lambda^2-1)}$, $\pi_i^B(G_1, G_2) = \frac{(1-c)(c+\lambda(1-z)-1)}{9(\lambda^2-1)}$ for all firm $i = \{1, 2\}$, $\pi_i^G(G_1, G_2) = \frac{(1-z)[(1-c)\lambda+z-1]}{9(\lambda^2-1)}$, $Q = \frac{2(1-c-\lambda(1-z))}{3(1-\lambda^2)}$, and $X = \frac{2(1-z-\lambda(1-c))}{3(1-\lambda^2)}$.

Only firm 1 develops a green good. The equilibrium in which only firm 1 produces green goods yields a social welfare,

$$SW_{G_1NG_2} = CS(Q) + CS(x_1) + \pi_1^B(G_1, NG_2) + \pi_1^G(G_1, NG_2) - K_1 + \pi_2^B(G_1, NG_2) - d\left(Q^2 + \alpha x_1^2\right)$$

where $CS(Q) = \frac{[4+c(\lambda^2-4)-\lambda A][2cB+4+\lambda(3z-\lambda)]}{72(1-\lambda^2)^2}$ where $A \equiv 3(1-z) + \lambda$ and $B \equiv (1 + 2\lambda)(\lambda - 2)$.

In addition, $CS(X) = \frac{[1+c(\lambda-2)][3+cC-\lambda(\lambda A-4)]}{24(1-\lambda^2)^2}$ where $C \equiv \lambda^3 - \lambda - 6$. Profits are $\pi_1^B(G_1, NG_2) = \frac{D[c(2+\lambda^2)-2-\lambda(\lambda-3(1-z))]}{36(1-\lambda^2)^2}$, where $D \equiv 2 - 5\lambda^2 + 2c[\lambda(3+\lambda) - 1] - 3\lambda z$, and $\pi_2^B(G_1, NG_2) = \frac{(c-1)D}{18(\lambda^2-1)}$ from the brown product, and

$$\pi_1^G(G_1, NG_2) = \frac{[1 + c(\lambda-2)][3 + cC - 6z + \lambda(\lambda(\lambda - 3(1-z)) - 4)]}{12(1-\lambda^2)^2}$$

from the green product for the only firm that develops such a good (firm 1). Finally, aggregate output levels are $Q = \frac{2+(\lambda-3)\lambda+3\lambda z-(2+\lambda^2)c}{6(1-\lambda^2)} + \frac{1-c}{3}$, and $X = \frac{1-c-(1-\lambda)c}{2(1-\lambda^2)}$.

Only firm 2 develops a green good. In this case, social welfare is given by

$$SW_{NG_1G_2} = CS(Q) + CS(x_2) + \pi_1^B(NG_1, G_2) + \pi_2^B(NG_1, G_2) + \pi_2^G(NG_1, G_2) - K_2 - d\left(Q^2 + \alpha x_2^2\right)$$

and hence $SW_{NG_1G_2} = SW_{G_1NG_2}$.

No firm develops a green good. Finally, when no firm produces green goods social welfare is just given by

$$SW_{NG_1NG_2} = CS(Q) + \pi_1^B(NG_1, NG_2) + \pi_2^B(NG_1, NG_2) - dQ^2$$

where $CS(Q) = \frac{2(1-c)^2}{9}$, $\pi_i^B(NG_1, NG_2) = \frac{(1-c)^2}{9}$ for all firm $i = \{1, 2\}$, and aggregate output is $Q = \frac{2(1-c)}{3}$.

Welfare comparison. Comparing $SW_{G_1G_2}$ and $SW_{G_1NG_2}$, we obtain that $SW_{G_1G_2} > SW_{G_1NG_2}$ for all $K < K_a$, where

$$K_a \equiv \frac{1}{72A^2}\left[\begin{array}{c}\chi + c^2(36 - \lambda(-A(5\lambda+12)) + 2d(36 + \lambda(\lambda-11)(\lambda+4)))) + \phi + \\ z^2(32 - 23\lambda^2) - 16\alpha dA(4\lambda + 4z - 1) + \eta\end{array}\right]$$

where $A = (\lambda-1)(\lambda+1)$, $\chi = (5 + \lambda(-28 - \lambda(\lambda+3)(11\lambda+5) + 12d(\lambda-1)^2(1+\lambda))$, $\phi = -28z + 2\lambda z(26 + 6dA + \lambda(14 - 17\lambda))$ and $\eta = 2c(18 - 36z + -16\alpha dA(6+\lambda) + \lambda(19 - 8z + \lambda(8\lambda^2 + \lambda + 8\lambda z + 18z - 26 - 6d\lambda^2 + 6d)))$.

Similarly, comparing $SW_{G_1NG_2}$ and $SW_{NG_1NG_2}$, we obtain that $SW_{G_1NG_2} > SW_{NG_1NG_2}$ for all $K < K_b$, where

$$K_b \equiv \frac{1}{24A^2}[9 + \Phi - 12z + \lambda(-5\lambda + 4(z-3) + 12dA(\lambda + z - 1) - \lambda(7\lambda + 3(-4+z)(\lambda+z)) + \kappa]$$

where $\Phi = c^2(-12 + \lambda(4 - 9\lambda)A) + 12\alpha dA$ and $\kappa = 2c(-6 + 6\alpha d(\lambda-2)A + 12z + \lambda(17 - 8z + \lambda(-2 - 6dA - 6z + \lambda(8z + 8\lambda - 11))))$.

Finally, comparing $SW_{G_1G_2}$ and $SW_{NG_1NG_2}$, we obtain that $SW_{G_1G_2} > SW_{NG_1NG_2}$ for all $K < K_c$, where

$$K_c \equiv \frac{2(1 + B\lambda - z)(3d(\alpha - \lambda) + 2(z - \lambda B - 1))}{9A}$$

where $B = (c-1)$. ■

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