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Environmental tax in a green market

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Abstract

We examine the impact of an emission tax in a green market characterized by consumers' environmental awareness and competition between firms for both environmental quality and product prices. The unique aspect of this model comes from the assumption that the cost for an increase in quality is fixed. We show that the emission tax improves welfare, thanks to a decline in pollution and despite an accentuation of product differentiation. The higher the marginal environmental damage is, the higher the optimal tax will be. The optimal tax, however, becomes lower than the marginal damage when the market is not too large. Finally, when marginal environmental damage is not too low, the optimal tax leads to a green product monopoly.

1. Introduction

In its 2008 North America Environmental Report, Toyota, the car manufacturer, argues that they "*spend an average of nearly $1 million an hour on research and development to develop the cars and technologies of the future. To maintain our global environmental leadership, we will redouble our efforts and substantially increase research and development spending over the next decade*". Toyota's so-called *Prius* model, indeed, illustrates how research and development (R&D) is key to improving the environmental impact of a product. Similarly, eco-labeling products also result from R&D efforts of their manufacturers. In all these cases, fixed production cost increases with environmental quality, because R&D expenses are required to modify a production process that will generate less pollution.

Two main reasons explain why some firms accept such additional cost. Firstly, increasingly stringent environmental policies require or encourage them to change their production processes in order to make them more environmentally friendly. The history of environmental policies in Europe since 1990 illustrates this point. European countries have been implementing green tax reforms since early 1990. Since 2005, the creation of a carbon market has also added new constraints on polluting companies. These economic instruments are complemented by many environmental standards. Secondly, the rise in the ecological consciousness of consumers has given firms the opportunity to increase their market share with green products. The 2008 Eurobarometer indicates that 75% of the Europeans are "ready to buy environmentally friendly products even if they cost a little bit more" but that only 17% of them report having recently bought "products marked with an environmental label" (European Commission, 2008).

In this paper, we focus on a specific environmental policy - an emission tax – and its capacity to encourage firms to improve the environmental quality of their product, when competing in a green market. We assume that consumers differ in their ecological consciousness and, thus, in their willingness-to-pay for environmental quality. Polluting firms choose their abatement effort and the associated environmental quality offered on the market as well as the price of their products. Social welfare is not only determined by the consumers' surplus and the firms' profits but also by the environmental damage caused by the manufacturing of the firms' products, i.e. the negative externalities of pollution.

Whereas under perfect competition, the optimal taxation is equal to the marginal environmental damage, imperfect competition leads the regulator to reduce the tax below this threshold.[1] This is due to the necessity of taking into account the second market failure, imperfect competition, in addition to the first one, pollution externality. Barnett (1980) shows the link between the optimal tax and the price elasticity of demand in the monopoly case. Levin (1985), Ebert (1992), Requate (1993a, 1993b) and Simpson (1995) extend this result to a Cournot oligopoly in a market with homogeneous products. Katsoulacos and Xepapadeas (1995) prove on the contrary that the tax rate is higher than the marginal damage, when the number of firms corresponds to the second best optimum. Some articles address this question within the framework of vertical product differentiation. Lombardini-Riipinen (2005) introduces an emission

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[1] For a recent survey, see Requate (2007).

tax in addition to an *ad valorem* tax and shows that the environmental tax is then equal to marginal environmental damage. This result is explained by the fact that a uniform commodity tax is equivalent to a lump-sum tax in her model, because of three fundamental assumptions: a consumer buys only one unit of the good or none; the market is fully covered; and quality increases marginal production cost. To the best of our knowledge, no article so far has tried to extend this result when environmental quality involves fixed costs of research and development (R&D). Poyogo-Theotoky and Teerasuwannajac (2002) study the credibility of a tax on emission coefficient by unit of production (and not on total emission) in a model with fixed quality costs. Within a similar framework, Moraga-González and Padrón-Fumero (2002) study the effects of other environmental policies (unit emission standards, technology subsidies and product tax) on pollution and social welfare. We extend this analysis to an emission tax.

We demonstrate the welfare-increasing effect of an environmental tax, which achieves a decrease in overall pollution. This conclusion contrasts with those of Moraga-González and Padrón-Fumero (2002), who say that "aggregate emissions may increase as a result of government's regulation, due to the strategic responses of the firms." As expected, the optimal tax appears to be generally less than the marginal environmental damage. More surprisingly, this tax leads to a green monopoly when the marginal damage is not too low.

The rest of the paper is organized as follows. In section 2, we introduce the model. In section 3, we study the game equilibrium and impact of the emission tax on equilibrium qualities and prices. In section 4, we analyze tax effects on welfare components in order to deduce its global effect and its optimal level. Section 5 brings the paper to a conclusion.

2. The framework

Consumers view lower pollution from product production and consumption as an environmental characteristic of a product, which increases product quality (all other features of the products being equal). All consumers prefer green products but they differ in their willingness to pay for them. Products can thus be differentiated by their environmental quality. According to models of vertical product differentiation developed by Mussa and Rosen (1978), Shaked and Sutton (1982) and Motta (1993), each firm produces one variant of a product and decides on its price. Each consumer buys one unit of the product or none.

Consumer preferences are represented by a standard utility function $u(\theta)$ defined by:

$$u(\theta) = r + \theta q_i - p_i \tag{1}$$

with r the consumer's income (which is normalized to zero for simplification), θ the ecological consciousness parameter which is uniformly distributed over $\left[\underline{\theta}, \overline{\theta}\right]$ with a unit density function, θq_i willingness-to-pay for quality q_i and p_i the price of the product i.

Facing a "green" quality q_h and a "brown" quality q_l ($q_h > q_l$), the consumer with a parameter $\tilde{\theta} = p_l/q_l$ is indifferent between consuming the brown product at price p_l or no product, and the consumer $\hat{\theta} = (p_h - p_l)/(q_h - q_l)$ is indifferent between consuming the brown product q_l at price p_l or the green product q_h at price p_h. We assume that the

market is not covered ($\underline{\theta} < \tilde{\theta}$), so that the demand for the brown product is $d_l = \hat{\theta} - \tilde{\theta}$ and the demand for the green product is $d_h = \bar{\theta} - \hat{\theta}$.[2]

The firms' production costs are assumed to be independent of quantity, strictly increasing and convex in quality, with the quadratic form $c(q_i) = \frac{1}{2} c q_i^2$. The ecological quality of the product i is defined by abatement $q_i = \bar{e} - e_i$, where $\bar{e}$ is the maximal pollution by each firm and e_i pollution by firm i. Normalizing $\bar{e}$ to 1, we identify the environmental quality q_i as the abatement effort, in percentage, made by the firm i. Quality is then defined over the interval $[0,1]$. Moreover, we assume, in line with Arora and Gangopadhyay (1995), Bansal and Gangopadhyay (2003), Moraga-González and Padrón-Fumero (2002), Motta and Thisse (1999) and Poyago-Theotoky and Teerasuwannajac (2002), that abatement is achieved through an R&D investment, so that the quality improvement requires a fixed cost. Our model thus distinguishes itself from the Lombardini-Riipinen's one (2005). We consider that firms are subject to an emission tax τ_e. Their profits are thus defined by:

$$\pi_i = (p_i - \tau_e e_i) d_i - c(q_i) = (p_i - \tau_e(1 - q_i)) d_i - \frac{1}{2} c q_i^2 \qquad i = l, h \qquad (2)$$

We can establish a link between the emission tax and the unit tax as assumed by Delipalla and Keen (1992) and Pirtillä (1997): the emission tax can be broken down into a unit tax τ_e and an abatement subsidy $\tau_e q_i d_i$.

The competition between firms takes place in a two-stage game. In the first stage, they decide on the environmental quality q_i to produce. In the second stage, they choose prices p_i. We examine the game equilibrium in the next section.

3. The game equilibrium

3.1 The price subgame

The game is solved using backward induction in order to provide the subgame perfect equilibrium. In the second stage, firms compete in prices knowing the product qualities decided in the first stage. Maximization of the profit (2) with respect to price induces the following prices:

$$\begin{cases} p_h^* = \dfrac{2\bar{\theta} q_h (q_h - q_l) + \tau_e q_h (3 - 2q_h - q_l)}{4q_h - q_l} \\ \\ p_l^* = \dfrac{\bar{\theta} q_l (q_h - q_l) + \tau_e (2q_h + q_l - 3q_h q_l)}{4q_h - q_l} \end{cases} \qquad (3)$$

These prices lead to following demand functions:

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[2] This assumption is usual in a duopoly model of vertical product differentiation with fixed cost for quality improvement. It assumes that the space between $\underline{\theta}$ and $\bar{\theta}$ is sufficiently large.

$$\begin{cases} d_h^* = \dfrac{2(\overline{\theta} + \tau_e)q_h - \tau_e}{(4q_h - q_l)} \\[3mm] d_l^* = \dfrac{q_h\left((\overline{\theta} + \tau_e)q_l - 2\tau_e\right)}{q_l(4q_h - q_l)} \end{cases} \tag{4}$$

All other things being equal, the emission tax τ_e has two contradictory effects on demand: through its abatement subsidy component, it plays as a rise in the maximal ecological consciousness from $\overline{\theta}$ to $\overline{\theta} + \tau_e$; through its maximal pollution taxation effect, it tends to depress demand for each product.[3] The demand for the brown product remains thus positive as long as the relative taxation effect is sufficiently low in comparison with the abatement effort of the brown firm:

$$\gamma_e \equiv \frac{\tau_e}{\overline{\theta} + \tau_e} < \frac{1}{2}q_l \tag{5}$$

The taxation parameter γ_e measures the relative emission tax effect compared to the abatement subsidy effect of the emission taxation. Condition (5) is fulfilled when this parameter is less than half of the brown firm's abatement effort. This implies that the emission tax τ_e is less than half the maximal willingness-to-pay for the brown quality, including abatement subsidy $(\overline{\theta} + \tau_e)q_l$.

3.2   The quality subgame

In the first stage, firms decide on quality levels anticipating prices of the second stage. They also maximize the following profits, rewritten using equations (2), (3) and (4), with respect to qualities:

$$\begin{cases} \pi_h = (q_h - q_l)d_h^2 - \dfrac{c}{2}q_h^2 \\[3mm] \pi_l = \dfrac{q_l}{q_h}(q_h - q_l)d_l^2 - \dfrac{c}{2}q_l^2 \end{cases} \tag{6}$$

The maximization conditions are:

$$\begin{cases} \dfrac{\partial \pi_h}{\partial q_h} = \dfrac{(2q_h - \gamma_e)\left((4q_h - 7q_l)\gamma_e + (8q_h^2 - 6q_hq_l + 4q_l^2)\right)\overline{\theta}^2}{(1 - \gamma_e)^2(4q_h - q_l)^3} - cq_h = 0 \\[4mm] \dfrac{\partial \pi_l}{\partial q_l} = \dfrac{q_h(q_l - 2\gamma_e)\left((4q_h - 7q_l)q_hq_l + (8q_h^2 - 6q_hq_l + 4q_l^2)\gamma_e\right)\overline{\theta}^2}{(1 - \gamma_e)^2(4q_h - q_l)^3 q_l^2} - cq_l = 0 \end{cases} \tag{7}$$

In order to simplify these conditions, we operate a first variable substitution by denoting the differentiation index $\lambda \equiv q_h^*/q_l^*$ (with $\lambda \geq 1$). Both conditions (7) induce the following equality:

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[3] We can verify that introduction of a unit tax instead of an emission tax triggers only the second effect.

$$\left(2\lambda q_l - \gamma_e\right)\left(\left(4\lambda - 7\right)\gamma_e + 2\left(4\lambda^2 - 3\lambda + 2\right)q_l\right)\overline{\theta}^2 =$$
$$\left(q_l - 2\gamma_e\right)\left(\left(4\lambda - 7\right)\lambda + 2\left(4\lambda^2 - 3\lambda + 2\right)\gamma_e\right)\underline{\lambda}^2 \tag{8}$$

Without emission tax, condition (8) equates to a polynomial function of degree three $4\lambda^3 - 23\lambda^2 + 12\lambda - 8 = 0$ with only one real root greater than one, $\lambda_0 = 5.2512$. By substituting λ by λ_0 in one of the first order conditions (7), we obtain, as Motta (1993), the brown equilibrium quality $q_l^* = 0.0482\overline{\theta}^2/c$ and hence the green quality $q_h^* = \lambda_0 q_l^*$.[4] The qualities offered to consumers are differentiated, rise with the maximal ecological sensitivity $\overline{\theta}$ and decrease with the slope of the marginal cost curve c. The equilibrium prices also grow with $\overline{\theta}$ and fall with c: $p_h^* = 0.1077\overline{\theta}^3/c$ and $p_l^* = 0.0102\overline{\theta}^3/c$. Demand increases with $\overline{\theta}$: $d_h^* = 0.525\overline{\theta}$ and $d_l^* = 0.262\overline{\theta}$.[5]

When τ_e is positive, we cannot analytically express the equilibrium qualities. We therefore turn to numerical simulations (see section 3.3) or carry out an *ex post* analysis of the equilibrium. With this aim, we operate a second variable substitution by expressing the taxation parameter γ_e in terms of a percentage ρ of the *ex post* equilibrium low quality q_l^* ($\rho \equiv \gamma_e/q_l^*$, with $\rho \in \left[0, \frac{1}{2}\right]$). Since ρ is introduced into the analysis *after* the implicit determination of q_h^* and q_l^* in (7), it corresponds to a *variable substitution* and not to an endogenisation of γ_e. Thanks to this variable substitution, the following proposition holds.

Proposition 1. *When the emission tax parameter* $\gamma_e \equiv \tau_e/\left(\overline{\theta} + \tau_e\right)$ *is expressed in terms of a percentage* ρ *of the* ex post *brown quality* q_l^* *and* $\rho \in \left[0, \frac{1}{2}\right]$, *the differentiation index* $\lambda \equiv q_h^*/q_l^*$ *is the only real root* $\lambda(\rho)$ *of the polynomial function* $P(\lambda; \rho)$ *defined by:*

$$P(\lambda; \rho) \equiv 4\left(1 - 4\rho^2\right)\lambda^4 + \left(12\rho^2 + 8\rho - 23\right)\lambda^3 + 4\left(1 + \rho\right)\left(3 - 2\rho\right)\lambda^2$$
$$+ 4\left(\rho^2 + 2\rho - 2\right)\lambda + 4\rho - 7\rho^2 \tag{9}$$

— Please insert figure 1 —

For each value of ρ, $P(\lambda; \rho)$ has only one real root $\lambda(\rho)$ greater than unity (cf. figure 1a). $\lambda(\rho)$ is a convex function which reaches a minimum at $\lambda(0.06) = 5.1731$ and exceeds its initial value at $\rho = 0.13$ (cf. figure 1b).[6] For each value of ρ, we thus compute the unique associated value $\lambda(\rho)$ and then substitute $\lambda(\rho)q_l^*$ for q_h^* and ρq_l^* for γ_e in the second optimality condition (7). We therefore deduce the proposition 2 below.

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[4] Motta (1993) proves that these qualities are indeed Nash equilibrium.

[5] The market is indeed partly covered if $\underline{\theta} \leq \tilde{\theta}$, so that $\overline{\theta}/\underline{\theta} > 4.706$. Moreover, $q_l^* \leq q_h^* \leq 1$ if $\overline{\theta}^2/c \leq 1/0.2533 \approx 3.95$.

[6] Calculations and simulations were made with the software Mathematica. It is impossible to express the form of this root simply.

Proposition 2. *When the emission tax parameter $\gamma_e \equiv \tau_e / (\bar{\theta} + \tau_e)$ is expressed in terms of a percentage ρ of the* ex post *brown quality q_l^* and $\rho \in [0, \frac{1}{2}]$, the equilibrium brown quality q_l^* is implicitly defined by the following equation:*

$$G(q_l^*; \rho) \equiv (1 - \rho q_l^*)^2 q_l^* - \phi(\rho) \frac{\bar{\theta}^2}{c} = 0 \qquad (10)$$

$$\text{with } \phi(\rho) = \frac{(1 - 2\rho)\lambda(\rho)\left((4.\lambda(\rho) - 7)\lambda(\rho) + 2(4\lambda(\rho)^2 - 3\lambda(\rho) + 1)\rho\right)}{(4.\lambda(\rho) - 1)^3} \qquad (11)$$

and the equilibrium green quality is defined as $q_h^* = \lambda(\rho)q_l^*$.

The polynomial function $G(q_l^*; \rho)$ increases in q_l^* and has only one real root $q_l^*(\rho)$ lower than unity, the expression of which is given in appendix A1 (cf. figure 1c).[7] The brown quality $q_l^*(\rho)$ increases with the tax parameter ρ and reaches its maximum at $\hat{\rho} = 0.07$ (cf. figure 1d). Consequently, the green quality, defined by $q_h^* = \lambda(\rho)q_l^*$, may increase or decrease with ρ according to the relative importance of the contradictory effects of the differentiation index $\lambda(\rho)$ and the brown quality $q_l^*(\rho)$. We show in appendix A1 that these qualities are the only stable solution of the quality game. Moreover, a simulation of both first order conditions, presented in appendix A2, shows that our methodology allows us to select the one stable equilibrium. Although the formulation of the game equilibrium set out in proposition 2 allows us to outline the effects of key parameters of the game on firms' choices, only simulations enable us to study more thoroughly the implications of the emission tax on the game equilibrium.

3.3   The consequences of an emission tax

An analysis of the qualities at the game equilibrium is carried out by restricting the study to the duopoly case, in such a way that definition space of τ_e becomes $[0, \bar{\tau}_e]$.[8]

— Please insert figure 2 —

A tighter emission tax leads to an improvement in the brown quality q_l^* when τ_e remains lower than a given threshold $\hat{\tau}_e$, and to a deterioration beyond this threshold (figure 2a). This result is in line with the proposition 2: the maximal brown quality is obtained with a tax parameter $\hat{\rho} = 0.07$, which corresponds to an emission tax $\hat{\tau}_e = 0.004$ in our baseline scenario where $\bar{\theta}$ and c are equal to 1. Furthermore, a more stringent tax tends to enhance the high quality q_h^* (figure 2b). As a consequence, differentiation slightly decreases when τ_e is low but noticeably increases with τ_e for

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[7] $G(0; \rho) = -\phi(\rho)\bar{\theta}^2/c < 0$ while $\phi(0) > 0$, $\phi(\rho)$ is slightly increasing up to $\phi(0.06) = 0.049$, and then decreasing to zero for $\rho = 1/2$.

[8] For $\bar{\theta}$ and c equal to 1, $\bar{\tau}_e = 0.0085$. Obviously, this threshold rises with $\bar{\theta}$ ($\bar{\tau}_e = 0.0148$ for $\bar{\theta} = 1.2$, $\bar{\tau}_e = 0.0238$ for $\bar{\theta} = 1.4$, $\bar{\tau}_e = 0.0362$ for $\bar{\theta} = 1.6$, $\bar{\tau}_e = 0.0525$ for $\bar{\theta} = 1.8$) and decreases with c. It corresponds to a tax parameter $\bar{\rho} = 0.18$.

higher values. The differentiation index shape highlighted in the figure 1b corroborates this result: $\lambda(\rho)$ is minimum at $\rho = 0.06$ such as $\tau_e = 0.003$ in our baseline scenario.

A higher emission tax increases prices through its direct effect on production cost and its indirect impact on product differentiation. The deterioration of the quality q_l^*, beyond $\hat{\tau}_e$, however, acts in the opposite direction. For both products, the former effect is stronger than the latter, in such a way that the higher τ_e is, the higher prices will be (figure 2c and 2d).

Higher emission taxation also tends to reduce demand for brown (figure 2e) and for green quality when $\bar{\theta}$ remains relatively low (figure 2f). Several variants on this parameter show that when $\bar{\theta}$ is sufficiently high, the demand for the green variant can grow with the tax (see appendix A4). In this case, the improvement of the green quality is due to a more stringent tax offsetting the price effect. Therefore, green demand follows a bell-shaped curve for medium $\bar{\theta}$ and a rising curve for higher $\bar{\theta}$.

As a consequence, the profit of the brown firm decreases with the emission tax, becoming equal to zero for the tax $\bar{\tau}_e$ (figure 2g). By contrast, the profit of the green firm follows a U-shaped curve thanks to the higher quality of its product (figure 2h). As a result, a high pollution tax leads to a green product monopoly, for which the analysis is given in appendix A3.

We have shown that a low emission tax enhances the quality of both products, and hence the quality of the environment, but increases product differentiation. The contradictory impacts of the tax on both market failures raise the question of its effects on social welfare.

4. The second best optimum

In accordance with the literature on environmental economics, we assume that global pollution generates environmental damage and this corresponds to a monetary valuation of the impact of pollution on society as a whole (Baumol and Oates, 1988). The welfare function is defined in the following way:

$$W = CS_h + CS_l + \pi_h + \pi_l + GR - D \tag{12}$$

with CS_i the surplus of consumers purchasing the quality q_i, π_i the firm i's profit ($i=h,l$), GR the tax revenue and D the environmental damage function. The damage is assumed to be linear with respect to total emissions E. Let δ be the marginal environmental damage, the total damage is then defined by $D = \delta E$, with $\delta \geq 0$. We analyze the effects of the emission tax on each component of welfare before inferring its global impact.

— Please insert figure 3 —

The net surpluses of consumers of green and brown products are defined by:

$$CS_i = \int_{\underline{\theta}_i}^{\bar{\theta}_i} (\theta q_i - p_i) d\theta = \frac{1}{2} q_i d_i (\bar{\theta}_i + \underline{\theta}_i) - p_i d_i \quad i = h, l \tag{13}$$

with $\underline{\theta}_l = \tilde{\theta}$, $\bar{\theta}_l = \underline{\theta}_h = \hat{\theta}$ and $\bar{\theta}_h = \bar{\theta}$. An increase in the emission tax raises the brown quality (below $\hat{\tau}_e$) and the green quality but it induces higher prices. Surplus of both types of consumers is reduced because the price effect outweighs the quality effect (figures 3a and 3b).

As shown previously, a brown firm's profit decreases with the emission tax whereas a green firm's profit follows a U-shaped curve.

Pollution is defined by:

$$E = \left(1 - q_h^*\right)d_h^* + \left(1 - q_l^*\right)d_l^* = \frac{\overline{\theta}}{1 - \rho q_l^*} \frac{3\lambda - \rho(1 + 2\lambda) - \lambda(2\lambda + 1 - 3\rho)q_l^*}{(4\lambda - 1)} \tag{14}$$

A rise in the emission tax tends to reduce pollution thanks to an improvement in the ecological quality of products and a drop in the total demand (figure 3c). Nevertheless, the tax revenue, defined by $GR = \tau_e E$, grows with the tax (figure 3d).

— Please insert figure 4 —

The effects of the emission tax on global welfare are not *a priori* obvious. Welfare tends to grow with τ_e thanks to fiscal revenue supplement and pollution reduction, but the loss in consumers' surpluses and firms' profit act in the an opposite direction. For a very low marginal damage, welfare follows a concave curve where the maximum is reached for a tax τ_e^* lower than its maximal value $\overline{\tau}_e$ (figure 4).[9] If the marginal environmental damage is higher, welfare is a growing function of τ_e. The welfare is then maximal for the value $\overline{\tau}_e$. We indeed show in appendix A3 that green monopoly taxation is always welfare depressing.

Studies of environmental tax in non-competitive markets underline that the second-best optimum is reached with an emission tax lower than the marginal environmental damage. This result is generally verified in our framework. Obviously, when δ is higher than the maximal tax $\overline{\tau}_e$, the optimal tax is always lower than marginal damage. When δ is lower than the maximal tax $\overline{\tau}_e$, simulations with a range of values for $\overline{\theta}$ show that the optimal tax remains lower than marginal damage when $\overline{\theta}$ is not too high. For instance, when $\overline{\theta}$ is normalized to 1, the optimal environmental tax is always lower than the marginal damage, whatever δ may be (see footnote 9). However, a special case emerges when $\overline{\theta}$ is higher than a threshold, denoted $\overline{\overline{\theta}}$:[10] the fiscal revenue effect is then so great that the optimal environmental tax is positive even with a marginal damage equal to zero. As a consequence, an optimal tax higher than the small marginal damage may arise (cf. appendix A4).

Proposition 3. *The higher the marginal damage δ is, the higher the second-best optimal emission tax τ_e^* will need to be. A marginal damage threshold $\overline{\delta}$ and a ecological awareness threshold $\overline{\overline{\theta}}$ exist such that the optimal tax is lower than marginal damage if:*

(a) $\delta > \overline{\tau}_e$, then $\tau_e^* \leq \overline{\tau}_e < \delta$

(b) $\delta \leq \overline{\tau}_e$ and $\overline{\theta} \leq \overline{\overline{\theta}}$, then $\tau_e^* < \delta \leq \overline{\tau}_e$

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[9] In the baseline scenario, the welfare follows a concave curve if $\delta \leq 0.025$ and the maximum is reached for τ_e=0.002 ($\rho = 0.04$) if $\delta = 0.01$, τ_e=0.007 ($\rho = 0.14$) if $\delta = 0.02$ and τ_e=0.008 ($\rho = 0.18$) if $\delta = 0.025$.

[10] Our simulations show that $\overline{\overline{\theta}}$ is around 1.22 when c is equal to one.

(c) $\delta \leq \overline{\tau}_e$, $\overline{\theta} > \overline{\overline{\theta}}$ and $\delta \geq \overline{\delta}$, then $\tau_e^* < \delta \leq \overline{\tau}_e$

and the optimal tax is higher than the marginal damage if:

(d) $\delta \leq \overline{\tau}_e$, $\overline{\theta} > \overline{\overline{\theta}}$ and $\delta < \overline{\delta}$, then $\delta \leq \tau_e^* \leq \overline{\tau}_e$

Beyond a certain marginal damage, the optimal tax reaches its maximal value $\overline{\tau}_e$. The most polluting firm is also ejected from the market and the less polluting firm becomes a green product monopolist.

Thus an emission tax seems an efficient means to move the game equilibrium closer to the Pareto's optimum. In most cases, the optimal tax is lower than marginal damage. This environmental policy can lead to a green monopoly. The optimal tax is then the one that induces a kind of limit price strategy for the green monopoly.

5. Conclusion

Since Pigou's work, environmental tax has been considered as one of the most efficient environmental policies. In a competitive market, the optimal tax is equivalent to the marginal environmental damage and leads to a first best optimum. When polluters compete in a non-competitive market, the environmental tax generally remains an efficient instrument but the coexistence of two market failures for only one policy leads economists to advocate a tax that is less than the marginal damage. This tax allows the attainment of a second-best optimum.

In our paper, we have examined a new non-competitive case:
– environmental quality competition in green markets where consumers differ in their ecological consciousness, and thus in their willingness-to-pay for environmental quality;
– and, polluting duopoly that compete both in price and the environmental quality of their products in a vertically differentiated market.

Furthermore, we have focused on situations where the improvement of environmental quality requires R&D expenditure, and thus involves fixed costs. We have shown that an emission tax leads to a decrease in pollution, through an improvement in green, and, in some cases, brown quality. The tax is therefore successful at increasing overall welfare.

The higher the marginal damage is, the higher the optimal tax will need to be. But the optimal tax is also less than the marginal damage when the market is not too large. In the case of relatively high marginal environmental damage, the optimal emission tax leads to the eviction of the brown product firm by giving an advantage to the green product firm. This is counter to a policy of higher competition between firms. In consequence, it may be advisable to introduce an economical policy to reduce the inefficiency caused by the monopoly power of the green firm.

This paper completes the results from Lombardini-Riipinen (2005), who studies emission tax in the case of variable costs for quality improvement, and Moraga-González and Padrón-Fumero (2002), who consider the effects of unit emission standards, technology subsidies and product tax in the case of fixed costs for quality improvement. In order to extend our analysis, it may be useful to provide some comparative statics of environmental quality, prices and welfare. This requires resolving

difficulties arising from the introduction of a variable cost in a product-differentiation model with fixed cost for quality. This will soon be subject to further research.

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7. Appendix

A1. Conditions for existence of an equilibrium

We study here the first order conditions (7) of the quality subgame. The first equation of conditions (7) decreases with q_h:

$$\frac{\partial^2 \pi_h}{\partial q_h^2} = -\frac{8(q_l - 2\gamma_e)\left[2\gamma_e(q_h - q_l) + (q_l - 2\gamma_e)q_l + (5q_h - \gamma_e)q_l\right]\overline{\theta}^2}{(1 - \gamma_e)(4q_h - q_l)^2} - c < 0$$

as the first term in the numerator is positive and the term in brackets is positive. Moreover,

$$\left.\partial \pi_h / \partial q_h\right|_{q_h = 0} = \gamma_e\left(4\overline{\theta}q_l - 7\gamma_e\right)\!\Big/ q_l^2 > 0$$

when condition (5) is met. There is thus a solution $q_h^*(q_l)$ for the first equation (7)

The second equation of conditions (7) increases for low values of q_l and then decreases for large values of q_l. (figure A1) The second derivative of firm l's profit is:

$$\frac{\partial^2 \pi_l}{\partial q_l^2} = -\frac{2q_h\left[4\left(16q_h^3 - 16q_h^2 q_l + 6q_h q_l^2 - 3q_l^3\right)\gamma_e^2 - 4(5q_h + q_l)q_l^3\gamma_e - (8q_h + 7q_l)q_h q_l^3\right]\overline{\theta}^2}{(1 - \gamma_e)(4q_h - q_l)^2 q_l^3} - c$$

A solution exists if there is $\varpi > 0$ such that $\partial^2 \pi_l(\varpi)\big/\partial q_l^2 = 0$ and $\partial \pi_l(\varpi)\big/\partial q_l > 0$. Some numerical simulations allow us to show that two equilibria are possible. However, the first one, with the lowest quality, is not stable because firm *l*'s profit increases for a quality slightly higher than this point. Only the second one is then a stable solution of the second condition (7). Nevertheless, the existence of an equilibrium requires a tax parameter lower than a threshold $\overline{\gamma}_e$. This threshold is all the more high as the maximal marginal willingness to pay is high. For $\overline{\theta}$=1 and *c*=1, the threshold $\overline{\gamma}_e$ is equal 0.011.

Simulations in subsection A2 show that our methodology for game resolution enables us to select the stable equilibrium. The expression of the low quality at equilibrium is given by:

$$q_l^* = \frac{2}{3\rho} + \frac{2^{\frac{1}{3}}}{3\rho\left[-2 + 27\beta + 3^{\frac{1}{2}}\beta^{\frac{1}{2}}(-4 + 27\beta)^{\frac{1}{2}}\right]^{\frac{1}{3}}} + \frac{\left[-2 + 27\beta + 3^{\frac{1}{2}}\beta^{\frac{1}{2}}(-4 + 27\beta)^{\frac{1}{2}}\right]^{\frac{1}{3}}}{3 \cdot 2^{\frac{1}{3}} \cdot \rho} \quad \text{with } \beta = \rho\phi(\rho)\frac{\overline{\theta}^2}{c}$$
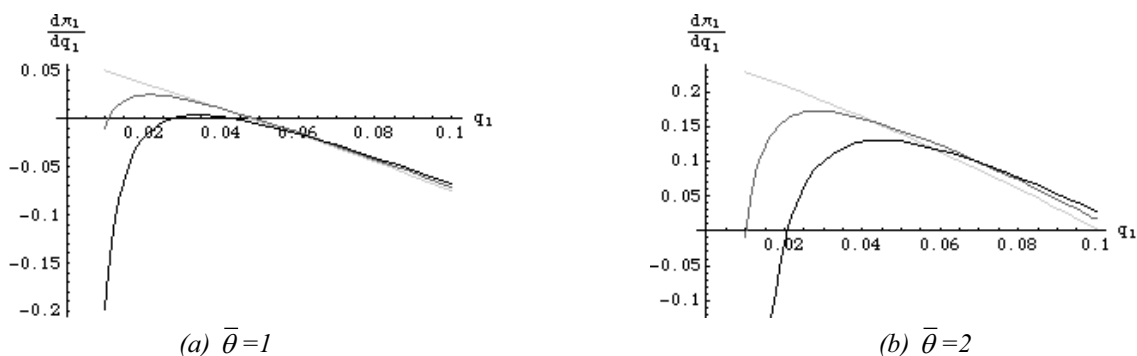
(a) $\bar{\theta}=1$ (b) $\bar{\theta}=2$

Figure A1. Simulation of $\partial\pi_1/\partial q_1$ for $q_h=0.25$

$\gamma_e=0$ *(clear grey curve), 0.005 (dark grey curve) and 0.01 (black curve)*

A2. Simulations of the game equilibrium

The assumption on the value of $\bar{\theta}$ affects the scale of the equilibrium qualities, prices and profits: the higher $\bar{\theta}$ is, the higher the qualities, the prices and the profits are. The assumptions on the values of c act in the opposite direction: the higher c is, the lower the qualities, the prices and the profits are. Without loss of generality in the analysis of the effects of the emission tax, all the model simulations are then made with the value 1 for $\bar{\theta}$ and c.

Tab. A1 Direct simulations of first order conditions

τ_e	**0**	**0.002**	**0.004**	**0.006**	**0.008**
γ_e	0	0.002	0.004	0.006	0.008
q_l^*	0.0482	0.0492	0.0492	0.0487	0.0472
q_h^*	0.2533	0.2542	0.2549	0.2556	0.2562
p_l^*	0.0102	0.0115	0.0126	0.0136	0.0144
p_h^*	0.1077	0.1090	0.1106	0.1125	0.1146
d_l^*	0.2625	0.2418	0.2210	0.1994	0.1754
d_h^*	0.5250	0.5243	0.5233	0.5220	0.5202
π_l^*	0.0015	0.0011	0.0007	0.0004	0.0001
π_h^*	0.0244	0.0241	0.0238	0.0237	0.0237

Tab. A2 Simulations of first order conditions with $\rho \equiv \gamma_e / q_l^*$

ρ	**0**	**0.04**	**0.08**	**0.12**	**0.18**
$\phi(\rho)$	0.0482	0.0488	0.0488	0.0482	0.0459
λ_0	5.2512	5.1837	5.1790	5.2419	5.4893
γ_e	0	0.0020	0.0039	0.0059	0.0084
q_l^*	0.0482	0.0490	0.0492	0.0487	0.0467
q_h^*	0.2533	0.2542	0.2549	0.2556	0.2563
p_l^*	0.0102	0.0114	0.0125	0.0135	0.0145
p_h^*	0.1077	0.1090	0.1106	0.1124	0.1152
d_l^*	0.2625	0.2421	0.2115	0.2007	0.1690
d_h^*	0.5250	0.5243	0.5234	0.5221	0.5196
π_l^*	0.0015	0.0011	0.0007	0.0004	0
π_h^*	0.0244	0.0241	0.0238	0.0237	0.0237

A3. The monopoly case

The emission tax can exclude the standard product firm from a green market. In that case, the green product monopoly faces demand $d_m = \bar{\theta} - p_m/q_m$ and determines price and quality that maximize its profit:

$$\pi_m = \frac{1}{\tau_v}\left(p_m - \tau_e(1-q_m)\right)\left(\bar{\theta} - \frac{p_m}{q_m}\right) - \frac{1}{2}cq_m^2$$

The optimal price is $p_m = \frac{1}{2}\left[\tau_e + \left(\bar{\theta} - \tau_e\right)q_m\right]$. It's an increasing function of quality if $\tau_e < \bar{\theta}$. Substituting the optimal price into the profit expression leads to the following profit equation:

$$\pi_m = \frac{\tau_e^2(1-q_m)^2 - 2\bar{\theta}\tau_e(1-q_m) + \bar{\theta}^2 q_m^2}{4q_m} - \frac{1}{2}cq_m^2$$

The optimal quality is then solution of the first order condition of profit maximization:

$$4cq_m^3 - \left(\bar{\theta} + \tau_e\right)^2 q_m^2 + \tau_e^2 = 0 \quad \text{or} \quad 4cq_m^3(1-\gamma_e)^2 - \bar{\theta}^2 q_m^2 + \bar{\theta}^2\gamma_e = 0.$$

Without emission tax, the monopoly produces the quality $q_m^0 = \bar{\theta}^2/4c$. With a positive emission tax, the optimal green quality of the monopoly is then defined by:

$$q_m^* = \frac{\beta_m}{3} + \frac{2^{\frac{1}{3}}\beta_m^2}{3\left[-2\beta_m^2 + 27\beta_m\gamma_e + 3^{\frac{3}{2}}\beta_m\gamma_e^{\frac{1}{2}}\left(-4\beta_m^2 + 27\gamma_e\right)^{\frac{1}{2}}\right]^{\frac{1}{3}}} + \frac{\left[-2\beta_m^2 + 27\beta_m\gamma_e + 3^{\frac{3}{2}}\beta_m\gamma_e^{\frac{1}{2}}\left(-4\beta_m^2 + 27\gamma_e\right)^{\frac{1}{2}}\right]^{\frac{1}{3}}}{3.2^{\frac{1}{3}}}$$
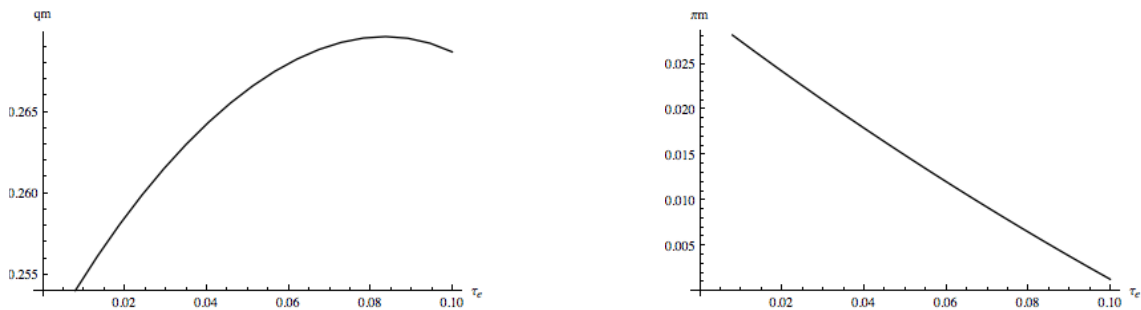
with $\beta_m = \dfrac{\bar{\theta}^2}{4c(1-\gamma_e)^2}$.

Figure A3. Monopoly's quality and profit for $\bar{\theta}/c = 1$

Some numerical simulations allow us to show that q_m^* increases with γ_e until a given threshold and then decreases, the demand for green product and the monopoly's profit decrease with γ_e. As a consequence, all components of welfare except government revenue tend to decrease with γ_e in such a way that the emission tax is welfare decreasing.

A comparison between welfare levels in the duopoly case and in the monopoly case highlights that the optimal emission is the one that ousts the brown firm when marginal damage is sufficiently high.
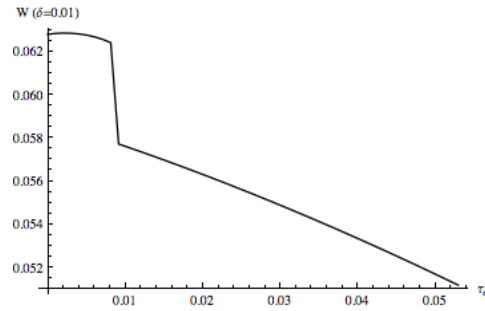
Figure A4. Welfare for δ = 0.01

A4. Variations of $\bar{\theta}$ [11]

$\bar{\theta}=1.4$	$\bar{\theta}=1.8$
Figure A5.7a Welfare for δ=0.01	Figure A5.7 Welfare for δ=0.01

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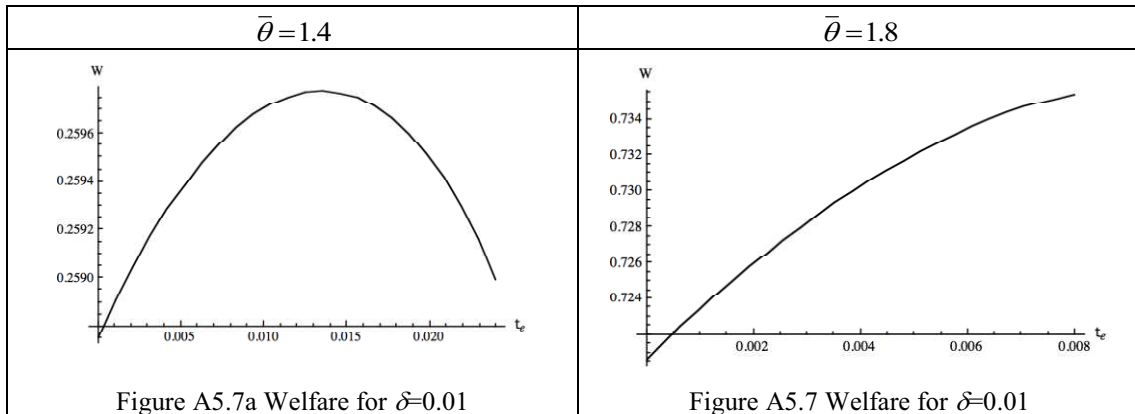
[11] Given the size of image files, only welfare results are reproduced here, but more results are available on request from the authors.

FIGURES

Figure 1. Optimality conditions of the quality game

Figure 1a. *P(λ; ρ)=0*
(The more the curves are dark, the more ρ tends to 1/2)

Figure 1b. *Solutions of P(λ; ρ)=0*

Figure 1c. $G\!\left(q_l^*;\rho\right)$ *with* $\overline{\theta}^2\!/c=1$
(The more the curves are dark, the more ρ tends to 1/2)

Figure 1d. *Solutions of* $G\!\left(q_l^*;\rho\right)$ *with* $\overline{\theta}^2\!/c=1$

Figure 2. The effects of an emission tax τ_e (for $\overline{\theta}^2/c = 1$)

Figure 2a

Figure 2b

Figure 2c

Figure 2d

Figure 2e

Figure 2f

Figure 2g

Figure 2h

Figure 3. The effects of an emission tax on welfare components (for $\overline{\theta}^2/c = 1$)

Figure 3a. Brown consumers' surplus

Figure 3b. Green consumers' surplus

Figure 3c. Pollution

Figure 3d. Tax Revenue

Figures 4. The global effect of an emission tax τ_e on welfare (for $\overline{\theta}^2/c = 1$)

Figure 4a. with δ=0.01

Figure 4b. With δ=0.02