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Abstract

This paper considers a market with an incumbent monopolistic firm and a potential entrant. Production by both firms causes polluting emissions. The government selects a tax per unit emission by maximizing social welfare. The size of the tax rate affects whether or not the potential entrant enters the market. We identify the conditions that create a market structure where the preferences of the government and the incumbent firm coincide. Interestingly, there are cases where both the government and incumbent firm prefer a monopoly. Hence, the government might induce profitable monopolization by using a socially optimal tax policy instrument.

Keywords: taxes, market structure, environmental pollution, monopoly
JEL classification: H23, L12, Q58

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1 Introduction

Over the last couple of decades environmental policy has become a major device in addressing and shaping industries' use of environmental and natural resources. In this respect, two important issues come forward: (i) the (optimal) relationship between environmental policy and market structure, i.e. the number of firms within a market (e.g., Buchanan 1969; Barnett 1980; Misiolek 1980; Baumol and Oates 1988; Katsoulacos and Xepapadeas 1995)[1], and (ii) who the winners and losers of environmental policy are (e.g., Jordan 1972; Buchanan and Tullock 1975; Maloney and McCormick 1982).[2] Environmental policy can be implemented in two ways, i.e. either by market-based instruments, like emission or effluent taxes, or by imposing direct command-and-control measures, like emission quotas or standards. Regarding issue (i), it is well known that taxes are superior to control measures in terms of achieving efficiency in pollution control activities. However, taxes might not be the preferred instrument when addressing issue (ii).

In their seminal article, Buchanan and Tullock (1975) compare effluent taxes and quotas and argue that regulated industries tend to prefer quotas to effluent charges, since the former create a higher degree of "industry cartelization" (or "monopolization") and as such would yield higher industry profit. Dewees (1983) has also demonstrated that existing firms may prefer standards to market-based policies, such as taxes. The idea is that incumbent firms are not necessarily harmed by imposed environmental policy but can gain an advantage out of it. For instance, in a positive theoretical setting Maloney and McCormick (1982) show that environmental control measures may deliver rents to regulated firms. That is, the active pursuit by incumbent firms for more stringent regulation can be used as a strategic tool to "raising rivals' costs" (e.g., Salop and Scheffman 1983; Simpson 1995).[3] By raising the costs as induced by regulatory controls, output is reduced and prices subsequently tend to increase, which can generate higher profits in case entry is restricted. The theoretical prediction that environmental controls can act as an entry deterrence device has recently also found empirical

[1]See also Lee (1975), Conrad and Wang (1993), Shaffer (1995), Simpson (1995), Lee (1999) for theoretical contributions, and OECD (1995) for a general discussion of issue (i).

[2]See Pearson (1995) for a practical discussion of this issue and Farzin (2003, 2004) for a theoretical coverage of both issue (i) and (ii).

[3]Puller (2006) provides a recent study on how firms in a concentrated industry have an incentive to innovate so as to intensify the pursuit for more stringent environmental regulation in order to raise their rivals' costs.

support by the study of Helland and Matsuno (2003). They particularly find that larger firms may benefit from increased compliance costs. Thus, the above suggests that environmental control measures could lead to industry cartelization.

Given this important policy effect on industry structure and firm performance, our paper adds to the above literature by focusing specifically on environmental taxes. The aim is to examine under which conditions such taxes may create both a beneficial market outcome to the regulated industry and a beneficial welfare outcome to the government, where welfare includes an environmental quality argument. That is, we identify the conditions that create a market structure where the preferences of the government and the incumbent firm coincide, which implies a lower degree of competition in the market.

In a well-known article, Katsoulacos and Xepapadeas (1995) look at the effect of an effluent tax on the number of firms in an oligopolistic market setting. In the first stage of the game the government sets the (welfare-maximizing) tax rate. In the second stage, all firms decide whether or not to enter the industry, which is subsequently followed by competition in the output market. Shaffer (1995) and Lee (1999) do a similar exercise but then with an output tax instead of an effluent tax. The main difference with the aforementioned literature is that we address a market structure in which an incumbent firm is already active in the output market, whereas the previous literature considers the situation that *all* firms have to decide whether or not to enter the industry before they start producing. We believe that our setting is more appropriate in those cases where a government introduces environmental taxes in a market that already exists. Moreover, it enables us to examine whether or not an existing firm will benefit from environmental taxes.

Our model considers a market for a homogeneous good with an incumbent monopolistic firm and a potential entrant, where production by both firms causes polluting emissions (environmental wastes or effluents). The government selects a tax per unit of emission by maximizing social welfare. Social welfare also takes into account the social damage caused by the aggregate industry pollution. The magnitude of the emission tax affects the potential entrant's decision whether or not to enter the market. In particular, we investigate the following three-stage game. In the first stage, the emission tax is chosen by the government. In the second stage, the potential entrant decides whether or not it will enter the market.

Finally, given the decision of the potential entrant in the second stage, either the incumbent firm supplies the monopoly output level in case entry did not occur or both firms compete in outputs in case of entry.

Interestingly, we show that there are cases where both the government and the incumbent firm prefer to establish the low monopoly output by introducing a relatively high emission tax. In that case, the government deliberately induces profitable monopolization of the market. Hence, in contrast to the aforementioned finding of Buchanan and Tullock (1975), we show that a market-based instrument in the form of environmental taxes can also effectively lead to monopolization of the market. From the industry perspective, the incumbent firm may prefer a high emission tax if it creates an entry barrier, hence providing more leeway to reap the fruits (higher profit) from a higher degree of industry concentration. Moreover, the government may as well prefer less competition because this could cause less damage to the environment, which has a positive effect on social welfare.

The paper is organized as follows. Section 2 describes the model. Section 3 presents the results derived from the model. Section 4 gives a numerical illustration. We conclude in Section 5. Proofs and technical details are given in the Appendix.

2 The model

Take a market with an incumbent firm (firm 1) and a potential entrant (firm 2). Both firms supply a homogeneous product. The inverse demand function is $p = a - bQ$, where p denotes the price, $Q = q_1 + q_2$ is output, and $a, b > 0$ are constants. Firm 2 incurs a fixed entry cost $F > 0$. Production costs of both firms are normalized to zero. Production of one unit of output causes $e > 0$ units of polluting emissions. The government imposes a tax $\tau \geq 0$ per unit of emission. The tax rate is set by maximizing social welfare W, comprising producer surplus (aggregate profits net of taxes) PS, consumer surplus CS, aggregate tax revenues T, and the social valuation of environmental damage caused by aggregate pollution D:

$$W = PS + CS + T - D. \tag{1}$$

We write $T = \tau eQ$ and $D = \lambda eQ$, with $\lambda > 0$ denoting the marginal social damage of environmental pollution (see also Moraga-González and Padrón-Fumero 2002).

We employ a three-stage game to analyze the impact of environmental taxation on social welfare and its subsequent effect on the market structure. In stage 1 the government selects the emission tax rate τ, in stage 2 firm 2 decides whether or not to enter and in stage 3 there is Cournot competition (if firm 2 decides to enter) or monopoly (if firm 2 decides not to enter). As usual in such a setting, the model is solved for the subgame-perfect Nash equilibrium.

We impose the following assumption on the parameters of the model:

Assumption 1 *There holds $\lambda_{min} < \lambda < \lambda_{max}$, with $\lambda_{min} \equiv \frac{a}{3e}$ and $\lambda_{max} \equiv \frac{a-2\sqrt{bF}}{e}$.*

If Assumption 1 does not hold, then either λ is so small that the government does not tax pollution at all in a duopoly, or λ is so large that the tax rate set by the government *always* precludes entry by firm 2. Clearly, these extreme cases are less interesting. Finally, remark that $\lambda_{min} < \lambda_{max}$ implies that $F < F_{max}$, with $F_{max} \equiv \frac{a^2}{9b}$. Hence, given a and b, the fixed entry cost must be small enough.

3 Results and discussion

We derive the equilibrium using backward induction. In the third stage the tax rate τ is given and two market cases need to be considered: monopoly and duopoly. It is straightforward to derive the first-order conditions and the equilibrium values for output, price and profit under both market configurations. The equilibrium values are given in Table 1. To ensure outputs are positive, we need $a - \tau e > 0$. It turns out that this holds in equilibrium.

In the second stage (again τ given) the entry decision of firm 2 is considered. Firm 2 enters the market if and only if its gross profit exceeds the fixed entry cost, i.e. if $\frac{(a-\tau e)^2}{9b} - F > 0$. Solving $\frac{(a-\tau e)^2}{9b} = F$, while focusing on the case with $a - \tau e > 0$, one obtains:

$$\tau = \overline{\tau} \equiv \frac{a - 3\sqrt{bF}}{e}. \tag{2}$$

Remark that $\overline{\tau} > 0$ if $F < \frac{a^2}{9b}$, which is true as a result of Assumption 1. Furthermore, as expected, $\overline{\tau}$ is a decreasing function of F. We now obtain:

Lemma 1 *Suppose Assumption 1 holds. Let the tax rate τ be given (with $a - \tau e > 0$). Then firm 2 will enter the market if $\tau < \overline{\tau}$; it will decide not to enter the market if $\tau \geq \overline{\tau}$.*

Table 1: Equilibrium monopoly and duopoly values.

	Monopoly	Duopoly
Output	$q^m = Q^m = \frac{a-\tau e}{2b}$	$q_1^d = q_2^d = \frac{a-\tau e}{3b}$
		$Q^d = \frac{2(a-\tau e)}{3b}$
Price	$p^m = \frac{a+\tau e}{2}$	$p^d = \frac{a+2\tau e}{3}$
Profit	$\pi^m = \frac{(a-\tau e)^2}{4b}$	$\pi_1^d = \frac{(a-\tau e)^2}{9b}$
		$\pi_2^d = \frac{(a-\tau e)^2}{9b} - F$

Notice that firm 2 will enter in case the government does not impose an emission tax.

Finally, in the first stage the governmental authority selects the tax rate τ, given the degree of pollution e. Let us first find the optimal tax rate given that firm 2 decides to enter. Then in the duopoly social welfare reduces to (see Appendix):

$$W^d = \frac{4(a-\tau e)^2}{9b} + \frac{2(a-\tau e)}{3b}(\tau - \lambda)e - F. \tag{3}$$

The government maximizes social welfare (3) under the constraint that firm 2 does enter, i.e. $\tau < \overline{\tau}$. Solving $dW^d/d\tau = 0$ yields:

$$\tau^d = \frac{3\lambda}{2} - \frac{a}{2e}. \tag{4}$$

Using Assumption 1 it follows that $0 < \tau^d < \overline{\tau}$. Hence, τ^d is the welfare-maximizing tax rate in the duopoly case. As expected, this optimal tax rate is increasing in the marginal social damage of pollution, λ. The tax rate is independent of F since the government now accommodates entry of firm 2 and the output decision of this firm is not affected by the fixed entry cost. We further notice that Assumption 1 implies that $a - \tau^d e > 0$, i.e. duopoly outputs are indeed positive.

Using the tax rate (4), the term $a - \tau^d e$ straightforwardly reduces to $\frac{3}{2}(a - \lambda e)$. Subsequent substitution of this expression into (3) generates the following simplified expression of social welfare under duopoly with the optimal tax rule (see Appendix):

$$W^d = \frac{(a-\lambda e)^2}{2b} - F. \tag{5}$$

Let us now consider the case where firm 2 decides *not* to enter. Social welfare then represents welfare under the monopoly structure, W^m:

$$W^m = \frac{3(a-\tau e)^2}{8b} + \frac{(a-\tau e)}{2b}(\tau - \lambda)e. \tag{6}$$

The government maximizes social welfare (6) under the constraint that firm 2 does not enter, i.e. $\tau \geq \overline{\tau}$. Solving $dW^m/d\tau = 0$, we find the solution:

$$\hat{\tau} = 2\lambda - \frac{a}{e}. \tag{7}$$

However, comparing the monopoly tax rate (7) with the optimal tax rate (4) set under a duopoly structure, it is easily seen that $\hat{\tau} < \tau^d < \overline{\tau}$, which, using Lemma 1, contradicts the assumption that firm 2 will not enter in this case. Hence, the constraint is binding and the government sets the tax rate $\tau = \tau^m \equiv \overline{\tau}$. Using this, social welfare in the monopoly case becomes (see Appendix):

$$W^m = \frac{3}{2}\sqrt{\frac{F}{b}}(a-\lambda e) - \frac{9F}{8}. \tag{8}$$

Remark that also here $a - \tau^m e > 0$, i.e. monopoly output is indeed positive.

For later use it is interesting to compare, while using the optimal tax rates, the profit level of firm 1 in case firm 2 does not enter with the profit level of firm 1 if firm 2 decides to enter. These profits are given by, respectively:

$$\pi^m = \frac{(a-\tau^m e)^2}{4b} = \frac{9F}{4}, \tag{9}$$

and

$$\pi_1^d = \frac{(a-\tau^d e)^2}{9b} = \frac{(a-\lambda e)^2}{4b}. \tag{10}$$

This leads us to the following result:

Lemma 2 *Suppose Assumption 1 holds. Then, under the optimal tax rules, the monopoly profit of firm 1 is larger than its duopoly profit, i.e.* $\pi^m > \pi_1^d$, *if and only if* $\lambda > \max\{\lambda_1, \lambda_{min}\}$, *with* $\lambda_1 \equiv \frac{a-3\sqrt{bF}}{e}$.

Proof. In Appendix. ■

It can be verified that $0 < \lambda_1 < \lambda_{max}$. However, λ_1 can be smaller or larger than λ_{min}.

We can solve for stage 1 by comparing social welfare with and without entry of firm 2. We derive the following result for the equilibrium decision of the government.

Lemma 3 *Suppose Assumption 1 holds. Then in equilibrium the government selects* $\tau = \tau^m \equiv \overline{\tau}$ *if and only if* $\lambda > \max\{\lambda_2, \lambda_{min}\}$*, with* $\lambda_2 \equiv \frac{a-(\frac{3}{2}+\sqrt{2})\sqrt{bF}}{e}$*. The government selects* $\tau = \tau^d$ *otherwise.*

Proof. In Appendix. ■

We observe that $0 < \lambda_1 < \lambda_2 < \lambda_{max}$, and that λ_2 can be smaller or larger than λ_{min}.

Combining the above Lemmas, we present our main proposition.

Proposition 1 *Suppose Assumption 1 holds. Define* $F_1 \equiv \frac{4a^2}{81b}$ *and* $F_2 \equiv \frac{16a^2}{9(3+2\sqrt{2})^2 b}$ *(with* $0 < F_1 < F_2 < F_{max}$*) and take* λ_1 *and* λ_2 *as defined in Lemma 2 and Lemma 3. We then have the following in equilibrium for different values of* $F \in (0, F_{max})$ *and* $\lambda \in (\lambda_{min}, \lambda_{max})$*:*

– Case (a): Let $0 < F < F_1$*. Then* $\lambda_{min} < \lambda_1 < \lambda_2 < \lambda_{max}$*, and*

(i) $\lambda_{min} < \lambda < \lambda_1 \Rightarrow \tau = \tau^d$ *and* $\pi_1^d > \pi^m$*,*

(ii) $\lambda_1 < \lambda < \lambda_2 \Rightarrow \tau = \tau^d$ *and* $\pi^m > \pi_1^d$*,*

(iii) $\lambda_2 < \lambda < \lambda_{max} \Rightarrow \tau = \tau^m$ *and* $\pi^m > \pi_1^d$*.*

– Case (b): Let $F_1 < F < F_2$*. Then* $\lambda_1 < \lambda_{min} < \lambda_2 < \lambda_{max}$*, and*

(iv) $\lambda_{min} < \lambda < \lambda_2 \Rightarrow \tau = \tau^d$ *and* $\pi^m > \pi_1^d$*,*

(v) $\lambda_2 < \lambda < \lambda_{max} \Rightarrow \tau = \tau^m$ *and* $\pi^m > \pi_1^d$*.*

– Case (c): Let $F_2 < F < F_{max}$*. Then* $\lambda_1 < \lambda_2 < \lambda_{min} < \lambda_{max}$*, and*

(vi) $\lambda_{min} < \lambda < \lambda_{max} \Rightarrow \tau = \tau^m$ *and* $\pi^m > \pi_1^d$*.*

Proof. In Appendix. ■

To discuss Proposition 1, let us first develop some intuition. It can be verified that entry of firm 2 always leads to a lower price and higher industry output, resulting in a higher summation of (gross) profits, consumer surplus and tax revenues compared to the monopoly case. This has a positive effect on social welfare. On the other hand, both the fixed entry fee and higher aggregate environmental pollution adversely affect social welfare. Yet, if we take the extreme case where F and λ are small, these negative effects are less important and the government prefers duopoly, i.e. it sets $\tau = \tau^d$. Next, take the other extreme case where both F and λ are large. In that case, the adverse effects of the fixed entry fee and higher aggregate environmental pollution will dominate the positive effects of entry by firm 2, and the government will prefer monopoly, i.e. it sets $\tau = \tau^m$. This intuition explains what happens with the tax rate set by the government if we compare cases (i)—(vi) of Proposition 1 for gradually increasing values of F and/or λ.

Let us now focus on the effects of changes in F and λ on the profit of firm 1. Clearly, if we would have the same tax rate in monopoly and duopoly, firm 1 would prefer monopoly since then it faces no competition and can keep its higher monopoly profit. However, in our model, the tax rate in monopoly is larger than the tax rate in duopoly, i.e. $\tau^m > \tau^d$. Further, if F and/or λ become smaller, the difference between τ^m and τ^d becomes larger. In that case it might happen that the difference between the tax rates becomes so large, that firm 1 prefers duopoly with its relatively much smaller tax rate. This explains what happens with the profit of firm 1 in cases (i)—(vi) of Proposition 1 for different values of F and/or λ.

Next, let us examine the interest of the government jointly with the interest of the incumbent firm. We make three observations. First, we have identified the conditions where the governmental and firm 1's interests coincide in the sense of deterring entry of firm 2. These conditions are given by cases (iii), (v) and (vi) of Proposition 1, where the government prefers monopoly above duopoly and imposes a correspondingly high tax rate. This discourages entry of firm 2, which is profitable to firm 1, and a low monopoly output level can be established. Second, there are also situations where the interests of the government and firm 1 do not coincide. They are given by cases (ii) and (iv) of Proposition 1. Here the government prefers duopoly with its positive effects on social welfare, whereas firm 1 prefers monopoly, even though the tax rate would be higher in that case. Third, in case (i) the interests of the government and firm 1 coincide again, but now in the sense that both prefer duopoly. Given our discussion above the reason for this coincidence of interests is clear, i.e. F and λ are small in this case.

We notice that in order to simplify the presentation, we have not considered in Proposition 1 the cases where $F = F_1$, $F = F_2$, $\lambda = \lambda_1$ or $\lambda = \lambda_2$. The results for those cases are

Table 2: Outcomes for different values of λ with $a = 10$, $b = 2$, $e = 3$ and $F = 2$.

λ	W^m	W^d	π^m	π_1^d	π_2^d	D^m	D^d	τ^m	τ^d
1.30	6.90	7.30	4.50	4.65	2.65	5.85	11.90	1.33	0.28
1.35	6.67	6.85	4.50	4.43	2.43	6.08	12.05	1.33	0.36
1.40	6.45	6.41	4.50	4.21	2.21	6.30	12.18	1.33	0.43

obvious and less interesting, and can be left to the reader.

Concluding this section, we recall that it is common practice in the literature to compare the size of the emission tax rate with the marginal social damage caused by pollution (see e.g., Barnett 1980; Katsoulacos and Xepapadeas 1995). Using (4), we see that $\tau^d < \lambda$ if and only if $\lambda < a/e$, which is always true given Assumption 1. Intuitively, the government sets τ^d smaller than λ in order to mitigate the distortion that exists due to imperfect competition (market power) in the duopolistic output market (cf. the aforementioned references). Turning to τ^m, equation (7) yields that $\tau^m < \lambda$ if and only if $a - 3\sqrt{bF} < \lambda e$. Substituting $F = 0$ and invoking Assumption 1, we see that this inequality does not hold. On the contrary, if $F = F_{max}$, then the inequality is true. Hence, there exists a threshold $\hat{F}(\lambda)$ such that $\tau^m < \lambda$ if and only if $F \in (\hat{F}(\lambda), F_{max})$. Intuitively, if F is small, i.e. if $F \in (0, \hat{F}(\lambda))$, then the government sets a high tax rate in order to deter entry by firm 2, i.e. $\tau^m > \lambda$. However, if F is large, i.e. if $F \in (\hat{F}(\lambda), F_{max})$, then entry is already deterred for small tax rates and the government again tries to mitigate the output distortion on the monopolistic output market, i.e. $\tau^m < \lambda$.

4 An illustration

In order to give an illustration of the functional behavior of Proposition 1, let us fix some parameters and consider the situation where $a = 10$, $b = 2$, $e = 3$ and $F = 2$. As a result one obtains $\lambda_{min} = 1.11$, $\lambda_{max} = 2.00$, $F_{max} = 5.56$, $\lambda_1 = 1.33$, $\lambda_2 = 1.39$, $F_1 = 2.47$ and $F_2 = 2.62$. Notice that the fixed entry cost $F = 2$ implies that we are in case (a) of Proposition 1. For this case we take three different values of λ, which correspond to situations (i), (ii) and (iii) of Proposition 1 respectively. Table 2 contains the numerical outcomes of this specific example.

Comparison of the monopoly welfare (W^m) with duopoly welfare (W^d), and monopoly profit (π^m) with the profit of firm 1 in case of duopoly (π_1^d), shows that the results correspond to Proposition 1. The Table also presents for each value of λ the corresponding duopoly profit of firm 2 (π_2^d), the social valuation of environmental damage under monopoly ($D^m = \lambda e Q^m$) and under duopoly ($D^d = \lambda e Q^d$), and the monopoly and duopoly tax rates (τ^m and τ^d, respectively). Figures 1 and 2 below extend and complement Table 2 by showing how welfare (Figure 1) and profit of firm 1 (Figure 2) change as a function of $F \in [1.95, 2.05]$ and $\lambda \in [1.30, 1.40]$.

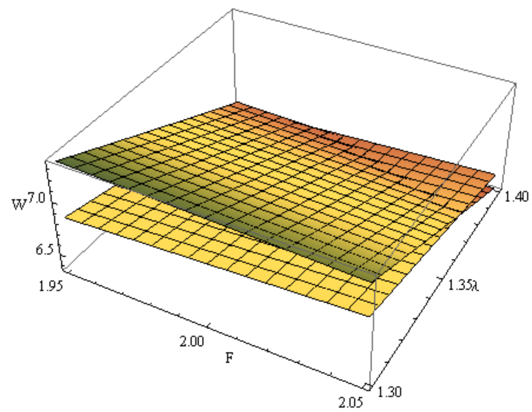

Figure 1: Monopoly and duopoly welfare as function of F and λ. The surface that hits the left front vertical axis above corresponds to duopoly welfare.

The impact of changes in F and λ on social welfare corresponds to the intuition. Recall that welfare under monopoly and duopoly are given by (8) and (5) respectively. In Figure 1 we see that welfare in the duopolistic market strictly decreases with F, which is relatively small in this specific example given the indicated range of parameter values. The influence of λ shows a stronger effect under duopolistic competition compared to the monopoly case. The reason here is that due to competition, output under duopoly is higher relative to the level of output under monopoly, and so the social valuation of environmental damage in the duopoly market is also higher than would be under monopoly, causing a stronger effect on duopoly welfare. Although welfare decreases at a faster rate under duopoly than under monopoly, Figure 1 also indicates that beyond a certain threshold value for λ monopoly welfare is higher than duopoly welfare.

The same rationale applies to the profit of firm 1 as presented in Figure 2. It indeed shows that the monopoly profit given by (9) is independent of λ but strictly increasing in F, whereas the duopoly profit given by (10) is independent of F but decreasing in λ. At a

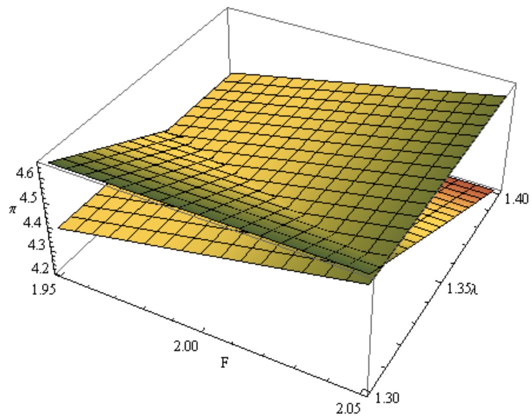

Figure 2: Monopoly and duopoly profit of firm 1 as function of F and λ. The surface that hits the left front vertical axis above corresponds to duopoly profit.

certain threshold value for λ profit under monopoly becomes higher than under duopoly.

5 Conclusions

It is known from the literature that direct environmental control measures, such as output quota of polluting products, might lead to monopolization or "cartelization" of markets, which is welcomed by the incumbent firm(s). This paper, instead, investigates this issue in terms of the use of a market-based environmental policy instrument, in particular an emission tax. We employ a three-stage game to identify the market conditions under which a government's preference and the preference of an incumbent monopolistic firm coincide in case of environmental taxation. Key in our analysis is to what extent the optimal tax rate set by the government affects the degree of competition, and subsequently the level of output. The incumbent firm might prefer a high emission tax if this discourages a potential rival to enter the market, which ensures the monopoly profit for the incumbent. The government might prefer such a high tax because of its discouraging effect on competition, hence keeping a monopoly in place, and implying less environmental damage. Depending on the marginal social damage of environmental pollution and the fixed entry cost of the potential entrant, less competition could imply higher overall welfare. In sum, a market-based social-welfare maximizing environmental tax instrument can also induce profitable monopolization of a market.

Appendix: Proofs and technical details

Derivation of social welfare function (3) under duopoly Producer surplus under a duopoly is just the sum of π_1^d and π_2^d. Taking the expressions from Table 1 yields $\frac{2(a-\tau e)^2}{9b} - F$. Consumer surplus reads:

$$\begin{aligned} CS &= \frac{1}{2}Q^d(a-p^d) \\ &= \frac{1}{2}\frac{2\,(a-\tau e)}{3b}\left(a - \frac{a+2\tau e}{3}\right) \\ &= \frac{2\,(a-\tau e)^2}{9b}. \end{aligned}$$

The aggregate tax revenues minus the social valuation of environmental damage becomes:

$$\begin{aligned} T - D &= Q^d(\tau-\lambda)e \\ &= \frac{2\,(a-\tau e)}{3b}(\tau-\lambda)e. \end{aligned}$$

Finally, combining the welfare terms according to (1) yields (3). ■

Derivation of social welfare function (5) under duopoly given optimal tax rule Using the optimal duopoly tax rate $\tau = \tau^d = \frac{3\lambda}{2} - \frac{a}{2e}$, the term $\frac{3}{2}(a-\lambda e)$ can straightforwardly be written as $\frac{3}{2}(a-\lambda e)$. Substitution of the latter into the social welfare function (3) then yields:

$$\begin{aligned} W^d(\tau^d) &= \frac{4}{9b}\cdot\frac{9}{4}(a-\lambda e)^2 + \frac{2}{3b}\cdot\frac{3}{2}(a-\lambda e)\left(\frac{3\lambda e}{2} - \frac{a}{2} - \lambda e\right) - F \\ &= \frac{(a-\lambda e)^2}{b} + \frac{(a-\lambda e)}{b}\cdot\frac{(\lambda e - a)}{2} - F \\ &= \frac{(a-\lambda e)^2}{2b} - F. \end{aligned}$$

We have found (5). ■

Derivation of social welfare function (8) under monopoly given optimal tax rule Using the optimal monopoly tax rate $\tau = \tau^m = \frac{a-3\sqrt{bF}}{e}$ and substituting this into (6) yields the social welfare function according to:

$$\begin{aligned} W^m(\tau^m) &= \frac{3}{8b} \cdot (9bF) + \frac{3\sqrt{bF}}{2b}\left(a - 3\sqrt{bF} - \lambda e\right) \\ &= \frac{27F}{8} + \frac{3}{2}\sqrt{\frac{F}{b}}\,(a-\lambda e) - \frac{9F}{2} \\ &= \frac{3}{2}\sqrt{\frac{F}{b}}\,(a-\lambda e) - \frac{9F}{8}. \end{aligned}$$

We have derived (8). ■

Proof of Lemma 2 Using (9) and (10), and invoking Assumption 1, one can verify that $\pi^m = \pi_1^d$ if $\lambda = \lambda_1 \equiv \frac{a-3\sqrt{bF}}{e}$. Together with Assumption 1 this gives Lemma 2. ■

Proof of Lemma 3 First, using (5) and (8) we have:

$$\begin{aligned} W^d &< W^m \Longleftrightarrow \\ \frac{(a-\lambda e)^2}{2b} - F &< \frac{3}{2}\sqrt{\frac{F}{b}}\,(a-\lambda e) - \frac{9F}{8} \Longleftrightarrow \\ \frac{(a-\lambda e)^2}{2b} + \frac{F}{8} &< \frac{3}{2}\sqrt{\frac{F}{b}}\,(a-\lambda e) \Longleftrightarrow \\ (a-\lambda e)^2 + \frac{bF}{4} &< 3\,(a-\lambda e)\sqrt{bF}. \end{aligned} \tag{1}$$

Next, introducing the auxiliary variable $x \equiv a - \lambda e$, we can rewrite (1) as:

$$x^2 - 3x\sqrt{bF} + \frac{bF}{4} < 0.$$

The roots of $x^2 - 3x\sqrt{bF} + \frac{bF}{4} = 0$ are equal to $x_{1,2} = (\frac{3}{2} \pm \sqrt{2})\sqrt{bF}$. Noting that Assumption 1 implies that $x > 2\sqrt{bF}$, we see that the relevant root is $x_1 = (\frac{3}{2} + \sqrt{2})\sqrt{bF}$. Hence, (1) is fulfilled for $2\sqrt{bF} < x < x_1$. Defining $\lambda_2 \equiv \frac{a-x_1}{e}$, and using Assumption 1, we obtain Lemma 3. ■

Proof of Proposition 1 Observe that $\lambda_{min} < \lambda_1$, or $\frac{a}{3e} < \frac{a-3\sqrt{bF}}{e}$, can be rewritten as $F < \frac{4a^2}{81b}$ ($\approx \frac{0.0494a^2}{b}$). Next, $\lambda_{min} < \lambda_2$, or $\frac{a}{3e} < \frac{a-(\frac{3}{2}+\sqrt{2})\sqrt{bF}}{e}$, can be rearranged as $F < \frac{16a^2}{9(3+2\sqrt{2})^2 b}$ ($\approx \frac{0.0523a^2}{b}$). Combining this with Lemma 2 and Lemma 3 yields Proposition 1. ■

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