J Regul Econ (2009) 36:94–106
DOI 10.1007/s11149-009-9093-4

ORIGINAL ARTICLE

Environmental taxes and industry monopolization

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Published online: 27 March 2009

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 of emission to maximize 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 Classifications H23 · L12 · Q58

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;

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Katsoulacos and Xepapadeas 1995; Carraro et al. 1996),[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] Regarding issue (i) it is well known that taxes are superior to command-and-control regulation 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) 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 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 command-and-control policies 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

[1] See also Lee (1975), Conrad and Wang (1993), Shaffer (1995, 2001), Simpson (1995) and Lee (1999) for theoretical contributions, and OECD (1995) for a general discussion of issue (i). In a seminal article Ellis and Fellner (1943) showed that market power alters the optimal tax in the presence of externalities in general.

[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.

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 to maximize 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. We conclude in Section 4. 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 to maximize 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:

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	$\pi^m = \frac{(a-\tau e)^2}{4b}$	$\pi_1^d = \frac{(a-\tau e)^2}{9b}$
		$\pi_2^d = \frac{(a-\tau e)^2}{9b} - F$

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

We write $T = \tau e Q$ and $D = \lambda e Q$, 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.

3 Results

3.1 The subgame-perfect Nash equilibrium

We derive the equilibrium using backward induction. In the third stage the tax rate $\tau \geq 0$ 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 the zero-profit condition $\frac{(a-\tau e)^2}{9b} = F$, 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 and only if $F < \frac{a^2}{9b}$, i.e., if the fixed entry cost is small enough given a and b.[4] Furthermore, as expected, $\overline{\tau}$ is a decreasing function of both F and e.

[4] Note that $\overline{\tau} = 0$ if $F = \frac{a^2}{9b}$. In that case firm 2 will never enter, which is uninteresting.

That is, if F and/or e increases, then the zero-profit condition is fulfilled for smaller $\overline{\tau}$. We now obtain:

Lemma 1 *Suppose $F < F_{max} \equiv \frac{a^2}{9b}$. 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 $\tau \geq \overline{\tau}$.*

Notice that Lemma 1 implies 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:

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

We now 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 $\lambda_{max} \equiv \frac{a-2\sqrt{bF}}{e}$.

Since we now examine the case where firm 2 decides to enter we need $\tau^d < \overline{\tau}$, which is equivalent with $\lambda < \lambda_{max}$. Furthermore, $\tau^d > 0$ if and only if $\lambda > \lambda_{min}$. In other words, if the latter inequality does not hold, then the government does not tax pollution at all in a duopoly. Clearly, this extreme case is less interesting. Remark also that Assumption 1 implies $\lambda_{min} < \lambda_{max}$, which in turn means that the condition $F < F_{max}$ of Lemma 1 is automatically satisfied.

It follows that 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, and the per unit emission, e. 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. Note 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}.

3.2 Main result

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 Lemmas 2 and 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. □

Figure 1 gives a graphical representation of the various (sub)cases of Proposition 1. It identifies the regions which correspond to cases (i)–(vi) for different values of the marginal social damage of pollution, $\lambda \in [0, a/e]$, and the fixed entry cost, $F \in [0, F_{max}]$. To get the functional relations as shown in the figure, we set $a = 10$, $b = 2$ and $e = 3$. Consequently F_1, F_2, $F_{\max}$ and λ_{min} are fixed. Then one can draw λ_1, λ_2 and λ_{max} as a function of the fixed entry cost. At $F = 0$, $\lambda_1 = \lambda_2 = \lambda_{max} = a/e$. Furthermore, we see that $\lambda_1 < \lambda_2 < \lambda_{max}$ for all $F > 0$. The relevant cases are all in the range $\lambda > \lambda_{min}$. Since F_1 and F_2 are close to each other, the regions where case (iv) and (v) hold are relatively small, as is case (ii). The regions that hold for case (i), (iii) and (vi) are biggest in size. To discuss Proposition 1 further, let us 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 aggregate profits, consumer surplus and tax revenues compared to the monopoly case. This has a positive effect on

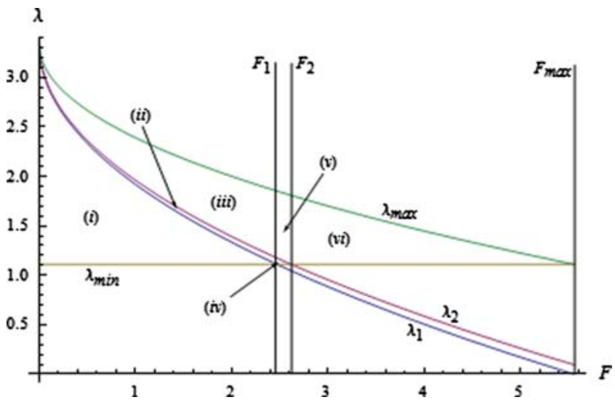

Fig. 1 Graphical representation of (sub)cases of Proposition 1

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 $\tau = \tau^d$. On the other hand, when the fixed entry cost is relatively large, say approaching F_{max}, then λ_{max} becomes close to λ_{min}. 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 obvious and less interesting.

3.3 Some additional remarks

To complete the analytical picture, let us compare the size of the emission tax rate with the marginal social damage caused by pollution, which is common practice in the literature (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 the (duopoly) tax rate lower than the marginal pollution damage 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, Eq. 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 in the monopolistic output market, i.e., $\tau^m < \lambda$.

One of our simplifications comprised the normalization of production costs to zero. Although this variable does not affect the optimal tax rates in our version of the model, they can easily be included. For instance, assume that both firms have the same constant marginal production costs, $c > 0$. Furthermore, suppose that the inverse demand function is given by $\tilde{p} = \tilde{a} - bQ$. Analyzing this modified model is formally equivalent to analyzing our original model if we write the demand intercept as $a = \tilde{a} - c$ and the price as $p = \tilde{p} - c$. In other words, we now interpret the price p in the original model as the price net of marginal production costs (see also Amir and Jin 2001).[5] Substitution of $a = \tilde{a} - c$ in (2) and (4) gives expressions of the optimal tax rates depending on the marginal production costs as well. Using (2) the effect of a change in the marginal production costs on the monopoly tax rate is $d\tau^m/dc = -1/e < 0$; employing (4) we find for the duopoly case $d\tau^d/dc = 1/(2e) > 0$. Let us first provide the intuition for the former result. Recall that the monoply tax rate is determined by the zero-profit condition of the potential entrant (firm 2). Now, if marginal production costs c increase, then, at a constant tax rate, firm 2's profit goes down. This implies that the monopoly tax rate fulfilling the zero-profit condition can decrease. With respect to the second comparative statics result, note that the optimal tax rate under a duopoly is determined by the government's welfare maximization problem (3). Now suppose again that the marginal production costs c increase. Then, keeping the tax rate

[5] For example, in the monopoly case the profit of firm 1 can be written as $pQ - \tau eQ = (\tilde{p} - c)Q - \tau eQ$.

constant, the duopoly price goes up and total output goes down, which leads to a decrease of social welfare. In order to mitigate this negative impact on welfare the government will accordingly adjust the duopoly tax rate in an upward fashion, since this increases aggregate tax revenues net of the aggregate social damage caused by pollution $(T - D)$.

As a final remark, note that our analysis concentrated on a linear modeling structure. However, the same modelling routine was conducted for a quadratic environmental damage function of the form $D = \lambda(eQ)^2$ (see also Poyago-Theotoky and Teerasuwannajak 2002). Again employing backward induction, the results of stages 3 and 2 remain unaffected for this modified environmental damage function, hence Lemma 1 and the equilibrium values as included in Table 1 still apply. It further appears that qualitatively, i.e., under appropriate changes of the relevant thresholds, Lemmas 2 and 3 as well as our main Proposition 1, also hold for the quadratic specification of the damage function.[6]

4 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. Such a situation is usually welcomed by the industries' 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 the subsequent output level. 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.

One should be cautious in generalizing the results given the linear properties of the model. On the other hand, allowing for a non-linear specification of demand, output and environmental damage comes at the cost of analytical tractability, however. We nevertheless were able to analytically solve the model for a quadratic specification of the environmental damage function and qualitatively all the results derived in this paper hold for such a case as well. Allowing for additional non-linear modeling features is left for future research.

[6] The formal proofs of these results are available from the authors upon request.

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 $a - \tau^d e$ 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:

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

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

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:

$$\begin{aligned} & W^d < W^m \\ & \iff \frac{(a-\lambda e)^2}{2b} - F < \frac{3}{2}\sqrt{\frac{F}{b}}\,(a-\lambda e) - \frac{9F}{8} \\ & \iff \frac{(a-\lambda e)^2}{2b} + \frac{F}{8} < \frac{3}{2}\sqrt{\frac{F}{b}}\,(a-\lambda e) \\ & \iff (a-\lambda e)^2 + \frac{bF}{4} < 3\,(a-\lambda e)\sqrt{bF}. \end{aligned} \tag{A1}$$

Next, introducing the auxiliary variable $x \equiv a - \lambda e$, we can rewrite (A1) 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, (A1) 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 Lemmas 2 and 3 yields Proposition 1. □

Acknowledgment We thank Allard van der Made and two anonymous referees for their helpful suggestions. The usual disclaimer applies.

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