Managerial Delegation Contracts in a Cournot Duopoly with Pollution*

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Abstract

We introduce an explicit environmental incentive into a managerial compensation contract under an emissions tax regime in the context of a Cournot duopoly with pollution externalities. We show that, depending on the effectiveness of "green" R&D, compared to a standard sales compensation contract, a manager conducts more abatement. As a consequence, the regulator sets a lower emissions tax, and social welfare is higher. Moreover, in general, firm owners earn higher profits when using the environmental delegation contract.

Keywords: Abatement, Emissions taxation, Managerial delegation, "Green" R&D, Cournot duopoly.

JEL numbers: H23, L1, M5, Q58.

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1 Introduction

Due to increasing public pressure to curb pollution, many firms are adopting corporate environmentalism and engage in emission-reducing activities. For example, since 2008 Intel has incorporated environmental-based performance into employees' compensation packages and evaluates performance based on environmental sustainability metrics that cover energy efficiency, reductions in greenhouse gas emissions (GHG), energy-use, and improving the firm's reputation as an environmental leader. In 2011, DSM, a Dutch-based multinational life sciences and material sciences firm, included GHG reduction targets as a long-term incentive in evaluating its executive compensation. Environmental stewardship accounts for one-third of the executive compensation in Xcel Energy where performance measures include a number of indicators such as increasing the amount of renewable energy available for commercial operations, reducing emissions, improving energy efficiency and integrating new abatement technologies.[1]

While shareholders and investors are concerned with the long-run sustainability of their companies and hence the exposure to climate change risks, corporate managers are generally more concerned about short-run profits to which their remuneration is pegged to during their tenure.[2]

Using incentive-based executive compensation to promote better environmental performance is a form of 'self-regulatory' initiative that is relatively new and being progressively adopted by firms. In light of the Paris Agreement on climate change, one would expect an increased emphasis on compensation packages that account for environmental sustainability. Thus the question we address in this paper is this: does a compensation package that includes environmental awareness[3] improve on the standard managerial compensation contract? We do this by considering a Cournot duopoly with pollution, where an emission tax is used to address the environmental externality. Firms owners/shareholders, whose aim is to maximise profits, engage managers who are entrusted with taking decisions on production and abatement. We compare two different com-

[1]See Strandberg (2013) for details on how firms have adopted environmental payment into executive compensation.

[2]In a recent annual meeting of Chevron, the Chief Executive Officer (CEO) John Watson revealed that there will be no major shift towards any environmental sustainability practices, despite a shareholder proposal to redirect capital away from costly high-carbon extraction projects. Source: `http://www.bloomberg.com/news/articles/2015-05-27/exxon-ceo-says-it-won-t-give-lip-service-on-climate` (assessed on 31 December 2016).

[3]Environmental awareness can take a variety of forms but we concentrate here on abatement activity targeted to curb production-related emissions.

pensation schemes: (i) a standard managerial delegation contract[4] where the incentive contract is based on a combination of profit and sales and (ii) a novel environmental delegation contract which rewards, in addition to profit, abatement activities. The emission tax operates here as the policy-driving force for firms to adopt the environmental-incentive contract. This is in addition to its role, as a market-based environmental instrument, in providing a clear-cut and predictable emissions price signal to firms that is relatively easy to implement compared to similar policies such as in cap-and-trade systems.[5] Furthermore, some developed countries including Denmark, Finland, Sweden, and the UK, have implemented a carbon tax, and this provides an empirical foundation on how an environmental-incentive copensation scheme can be used as a tool to achieve better welfare outcomes.[6]

The key results we obtain are as follows: (1) firms' profits are higher under the environmental delegation contract relative to the standard profit-cum-sales delegation contract; (2) the optimal (in a second best sense) tax is lower in the environmental delegation case and (3) when "green" R&D is relatively difficult, the environmental delegation scheme results in higher abatement, higher output, lower emissions per unit of output and higher social welfare compared to sales delegation.

The paper is related to the literature on strategic managerial compensation where the modern corporation is characterized by a separation of ownership and management. Since operational decisions are primarily made by the manager, the owner needs to offer an incentive-based compensation contract to the manager so that his incentive is aligned with that of the owner.[7] Bárcena-Ruiz and Garzón (2002) and Pal (2012) examine strategic sales delegation in the context of environmental regulation and evaluate the emission tax rate relative to a situation where delegation is absent. However, none of these papers consider managerial compensation contracts that incorporate environmental issues directly. In contrast, we introduce strategic delegation that takes into account abatement directly and makes it a pivotal part of a manager's compensation package.

[4]The literature on strategic delegation started with the papers of Vickers (1985), Fershtman and Judd (1987) and Sklivas (1987).

[5]In fact, major oil companies, e.g, BP, Shell, and ExxonMobil, have publicly announced that an emissions tax in the form of a carbon price is their preferred choice if governments were to implement new environmental policies in the future.

[6]See World Bank carbon tax report `https://web.archive.org/web/20150331101834/http://www.worldbank.org/content/dam/Worldbank/document/SDN/background-note_carbon-tax.pdf`(accessed 31 December 2016).

[7]e.g., Fershtman and Judd (1987, 2006), Sklivas (1987), Bebchuk and Fried (2003), Mujumdar and Pal (2007), Schnedler (2008).

A different branch of literature, on corporate environmentalism, addresses similar issues but from a different angle. In the context of environmental management within firms, Gabel and Sinclair-Desgagné (1993) using a principal-agent model analyze a setting where the CEO is the principal who is unable to monitor the efforts of middle managers in managing environmental risks. They show that if environmental risk-reduction technology becomes more viable and the CEO is more eager to promote environmental risk-reducing activities compared to profit-increasing activities, then the monetary incentives to middle-managers for reducing environmental risks should become stronger. Goldsmith and Basak (2001) also provide a principal-agent model to analyze the effect of environmental diligence among managers (the agents) given that the firm's top management (the principal) wants to avoid penalties from environmental authorities; to do so, the principal offers an incentive wage contract based on environmental stewardship performance measured by indicators such as achieving IS014001 certification. Berrone and Gomez-Mejia (2009) analyzed the keywords that appear in public statements issued by U.S. firms and found evidence that CEOs are rewarded for pursuing environmental strategies in polluting industries.

The paper is organized as follows. Section 2 we present the formal model of managerial compensation describing both the standard sales delegation contract as well as the environmental delegation one. In Section 3 we compare the two schemes in detail. Finally in Section 4 we provide some concluding remarks. All proofs are relegated in the Appendix.

2 The Model

We consider a duopoly where the two firms produce a homogeneous good under a linear demand specification, $p = a - Q, Q = q_i + q_j, i \neq j, i, j = 1, 2$, where a is a measure of market size. Following Ulph (1996) and Petrakis and Xepapadeas (2001), production generates pollution, which is taxed at the rate t on emissions. Each firm can reduce its tax burden by undertaking environmental "green"R&D (abatement), x_i, to reduce its emissions. The cost function for firm i is additive separable and given by $c(q_i, x_i) = cq_i + (\gamma x_i^2/2)$ where c is the unit cost of production ($a > c$) and $\gamma > 0$ is a parameter capturing the efficiency of the R&D technology (or, the extent of decreasing returns in abatement R&D).[8]

[8]Note that we concentrate on abatement of the end-of-pipe variant. This end-of-pipe technology mitigates (net) emissions by adsorbing pollution at the end of the production process (e.g., flue gas desulfurization equipment and activated carbon adsorption equipment are end-of-pipe technologies.) Dijkstra and Gil-Moltó (2014) compare end-of-pipe and integrated

Firm's i (net) emissions are

$$e_i\left(q_i, x_i\right) = q_i - x_i \geq 0, \tag{1}$$

Hence firm i's profit is

$$\pi_i = pq_i - c\left(q_i, x_i\right) - te_i\left(q_i, x_i\right), \tag{2}$$

with emission taxation a linear function of net emissions. Total emissions are $E = \sum e_i\left(q_i, x_i\right)$, and the damage function is a quadratic function of emissions, $D = (1/2)E^2$. In what follows, we set $c = 0$ without loss of generality.

The manager of each firm makes decisions on output and R&D on behalf of the owners. Similar to Fershtman and Judd (1987) firms' owners offer "take it or leave it" linear incentive schemes to their managers. Manager i receives a payoff: $\Omega_i = \beta_i + B_i O_i$, $\beta_i, B_i > 0$, and O_i is the incentive scheme. We consider two different types of incentive scheme:

$$O_{i,ed} = \alpha_i \pi_i + (1 - \alpha_i) t x_i \text{ (environmental delegation, } ed\text{) or,} \tag{3}$$
$$O_{i,sd} = \alpha_i \pi_i + (1 - \alpha_i) p q_i \text{ (sales delegation, } sd\text{)} \tag{4}$$

where $\alpha_i \in (0, 1)$ is the incentive parameter chosen by owner i. Owner i sets the compensation package such that $\Omega_i = \bar{u}$, i.e., the manager gets his reservation utility, which is normalized to zero. Managers therefore maximize O_i (being risk neutral). We assume that the owners commit to the incentive scheme.[9]

Under environmental delegation (ed), the incentive scheme consists of a linear combination of profits (π_i) and tax savings (tx_i). The latter rewards the manager for undertaking abatement to reduce the firm's emission tax bill: the manager, by undertaking abatement and thus reducing emissions (for a given output) generates tax savings for the firm. To reward the manager for this abatement effort, the firm owners pay a proportion $1 - \alpha_i$ of the total tax savings tx_i as part of the manager's compensation. Under the standard sales delegation (sd), the incentive scheme is a linear combination of profits (π_i) and sales (pq_i).[10] In the sequel we present the analysis for these two incentive schemes

abatement technology in the context of the effect of the strictness of emission taxation on output production.

[9]This assumption is common to most delegation literature. In its absence, the managerial contracts would not act as commitment device (Katz 1991). Furthermore as argued by Fershtman and Judd (1987) incentive contracts are costlier variables to change than output, and therefore remain unaltered for a substantial amount of time (while output and abatement decisions as well as the emission are being changed) and are likely to be observed by rivals.

[10]See Bárcena-Ruiz and Garzón (2002) and Pal (2012). Both papers use a different order

by solving for the Subgame Perfect Nash Equilibrium the following three-stage game(s) by backward induction: (i) In the first stage, the owners of the two firms simultaneously and independently set the incentive scheme of their managers (either *ed* or *sd* for both managers); the contracts cannot be renegotiated and become common knowledge; (ii) in the second stage the managers and the regulator *simultaneously* decide on the abatement effort and the emission tax respectively and (iii) in the third stage the managers simultaneoulsy and independently choose output.

We take the view here that incentive contracts are designed in the first stage before the environmental regulator sets the emission tax level to highlight the notion that contract design is a costly process and potentially has a longer-term horizon than setting/changing the emission tax.[11] Furthermore, to abstract from time-consistency issues in the setting of the emission tax relative to the choice of abatement by the firms/managers and associated strategic considerations, we let the regulator decide on the emission tax at the same time as firms decide on their abatement (in the second stage of the game).[12] Finally, by allowing the output choice to occur in the final stage of the game, we posit that output choice is a short-run decision while abatement choice is more longer-term decision.

2.1 Environmental Strategic Delegation

In the third stage of the game, each manager chooses the output level, q_i, that maximises $O_{i,ed} = \alpha_i \pi_i + (1-\alpha_i)tx_i = \alpha_i[pq_i - (1/2)\gamma x_i^2 - t(q_i - x_i)] + (1-\alpha_i)tx_i$, taking as given the incentive parameter, α_i, the emission tax, t and the abatement level, x_i. Solving these problems, from the first-order condition, $\alpha_i(A - 2q_i - q_j - t) = 0$ and by symmetry, i.e. $q_i = q_j = q$, we obtain

$$q(t) = \frac{A-t}{3}, i, j = 1, 2; i \neq j; \pi_i = [q(t)]^2 + tx_i - \frac{1}{2}\gamma x_i^2. \tag{5}$$

In the second stage, the managers select their abatement efforts simultaneously with the regulator who sets the emission tax level. Manager i taking t as given

of moves to the present paper in that the emission tax is set at the outset by the regulator.

[11]In the case of the environmental delegation incentive scheme, firms strategically signal their environmental commitment publicly so that the regulator will set a lower emissions tax rate after observing the managers' contracts.

[12]For a discussion of commitment versus time-consistency issues in the setting of the emission tax see, for example, Petrakis and Xepapadeas (1999, 2001).

chooses abatement x_i to maximise

$$\max_{x_i} O_{i,ed} = \alpha_i \left[[q(t)]^2 + tx_i - \frac{1}{2}\gamma x_i^2 \right] + (1-\alpha_1)tx_i.$$

At the same time the regulator taking x_i, x_j as given, sets t to maximise welfare:

$$\max_{t} SW = \int_0^{2q} (A-y)\mathrm{d}y - \frac{\gamma}{2}\sum_i x_i^2 - \frac{1}{2}\left[2q - \sum_i x_i\right]. \tag{6}$$

From the first-order conditions, we obtain the best-response functions of the managers and the regulator respectively as follows:

$$x_i(t) = \frac{1}{\alpha_i}\frac{t}{\gamma}, i = 1, 2 \tag{7}$$

$$t(x_i, x_j) = \frac{A - 3(x_i + x_j)}{4}. \tag{8}$$

and solving these we obtain:

$$t(\alpha_i, \alpha_j) = \frac{A\alpha_i\alpha_j\gamma}{3(\alpha_i + \alpha_j) + 4\alpha_i\alpha_j\gamma} \tag{9}$$

$$x_i(\alpha_i, \alpha_j) = \frac{A\alpha_j}{3(\alpha_i + \alpha_j) + 4\alpha_i\alpha_j\gamma}. \tag{10}$$

Using (10) into (5) yields:

$$q_i(\alpha_i, \alpha_j) = \frac{A\left[\alpha_i + \alpha_j(1 + \alpha_i\gamma)\right]}{3(\alpha_i + \alpha_j) + 4\alpha_i\alpha_j\gamma}. \tag{11}$$

We can then state the following preliminary result.

Lemma 1 *Under environmental delegation,*

(i) the emissions tax is increasing in α_i, $i = 1, 2$

(ii) abatement effort is decreasing in α_i *and increasing in* α_j

(iii) firm output is decreasing in α_i.

Lemma 1, part(i) implies a strategic effect where the firms' choice of α_i affects the regulator's choice of emissions tax: the higher the weight placed on profit, the higher the emissions tax and vice versa. Hence, α_i provides a signal to the government on the firms' resolution to reduce emissions. Parts (ii) and (iii) are as intuitively expected, given strategic substitutability of both abatemen and output.

Finally, in the first stage the owner of each firm chooses the incentive parameter for his manager, α_i, that maximizes his firm's profit (expression (2). The relevant first-order conditions yield the best-response functions in (α_i, α_j) space:

$$\alpha_i = \frac{3 + \alpha_j(1 + 4\gamma)}{5 + 6\alpha_j\gamma}, i, j = 1, 2, i \neq j. \tag{12}$$

Note that best-response functions are positively sloped implying strategic complementarity in the setting of the incentive scheme weights.[13] Thus each owner reacts positively to each other's choice of α's. This result is in contrast to the standard strategic delegation under output competition and is a direct result of incentivising abatement activities explicitly taken together with Lemma 1, part (i).

Solving the first-order conditions (12) we obtain the (symmetric) equilibrium incentive parameters under environmental delegation[14]

$$\alpha_{ed} = 1 - \frac{2 + 4\gamma - \sqrt{2(2\gamma + 1)(\gamma + 2)}}{6\gamma} \tag{13}$$

Using the value of α_{ed}, we then obtain the equilibrium values of the emission tax, firm output and abatement.[15]

$$t_{ed} = \frac{A\left[\sqrt{2(2\gamma + 1)(\gamma + 2)} - 2\right]}{20 + 8\gamma} \tag{14}$$

$$q_{ed} = \frac{A\left[22 + 8\gamma - \sqrt{2(2\gamma + 1)(\gamma + 2)}\right]}{60 + 24\gamma} \tag{15}$$

[13]The derivative of (12) is $\frac{\mathrm{d}\alpha_i}{\mathrm{d}\alpha_j} = \frac{5+2\gamma}{(5+6\alpha_j\gamma)^2} > 0$.

[14]It can be shown that the associated second-order conditions are satisfied.

[15]Given the expressions for equilibrium quantity and abatement, the equilibrium net emissions are $e_{ed} = q_{ed} - x_{ed} > 0$.

$$x_{ed} = \frac{3A}{2\left[7 + 2\gamma + \sqrt{2(2\gamma+1)(\gamma+2)}\right]} \tag{16}$$

Notice that the equilibrium values depend crucially on the effectiveness of "green" R&D (parameter γ). Finally, equilibrium profit per firm and social welfare can be easily computed by substituting (14),(15) and (16) into (2) and (6).

2.2 Standard Sales Delegation

In the third stage of the game, each manager chooses the output level, q_i, that maximises $O_{i,sd} = \alpha_i \pi_i + (1-\alpha_i)pq_i = (p - \alpha_i t)q_i + \alpha_i x_i (t - \frac{\gamma x_i}{2}$, taking as given the incentive parameter, α_i, the emission tax, t and the abatement level, x_i. Solving these problems, from the first-order conditions, $(A - 2q_i - q_j - t\alpha_i) = 0$ and by symmetry, i.e. $q_i = q_j = q$, we obtain

$$q = \frac{A - t(2\alpha_i - \alpha_j)}{3}, i, j = 1, 2; i \neq j; \pi_i = q^2 + tx_i - \frac{1}{2}\gamma x_i^2. \tag{17}$$

In the second stage, the managers select their abatement efforts simultaneously with the regulator who sets the emission tax level. Manager i taking t as given chooses abatement x_i to maximise

$$\underset{x_i}{max}\, O_{i,sd} = \alpha_i \left[q^2 + tx_i - \frac{1}{2}\gamma x_i^2\right] + (1 - \alpha_i)pq.$$

At the same time the regulator taking x_i, x_j as given, sets t to maximise welfare:

$$\underset{t}{max}\, SW = \int_0^{2q} (A - y)\mathrm{d}y - \frac{\gamma}{2}\sum_i x_i^2 - \frac{1}{2}\left[2q - \sum_i x_i\right]. \tag{18}$$

From the first-order conditions, we obtain the best-response functions of the managers and the regulator respectively as follows:

$$x_i(t) = \frac{t}{\gamma}, i = 1, 2 \tag{19}$$

$$t(x_i, x_j) = \frac{A - 3(x_i + x_j)}{2(\alpha_i + \alpha_j)}. \tag{20}$$

and solving these we obtain:

$$t(\alpha_i, \alpha_j) = \frac{A\gamma}{6 + 2(\alpha_i + \alpha_j)\gamma} \tag{21}$$

$$x_i(\alpha_i, \alpha_j) = \frac{A}{6 + 2(\alpha_i + \alpha_j)\gamma}. \tag{22}$$

Using (22) into (17) yields:

$$q_i(\alpha_i, \alpha_j) = \frac{A(2 + \alpha_j\gamma)}{6 + 2(\alpha_i + \alpha_j)\gamma}. \tag{23}$$

It then follows directly from the above:

Lemma 2 *Under sales delegation,*

(i) the emissions tax is decreasing in α_i *for* $i = 1, 2$,

(ii) abatement effort is decreasing in α_i, $i = 1, 2, i \neq j$,

(iii) firm output is decreasing in α_i *and increasing in* α_j.

Finally, in the first stage the owner of each firm chooses the incentive parameter for his manager, α_i, that maximizes his firm's profit (expression (2)). The relevant first-order conditions give:

$$\alpha_i = (2 - \frac{1}{\gamma}) - (\alpha_j + \frac{1}{2 + \gamma\alpha_j}), i, j = 1, 2, i \neq j, \tag{24}$$

with the best-response functions being negatively sloped whereby managers behave more agressively. Solving the first-order conditions (24) we obtain the (symmetric) equilibrium incentive parameters under sales delegation

$$\alpha_{sd} = 1 - \frac{5 + 2\gamma - \sqrt{9 + 4\gamma\,(1 + \gamma)}}{4\gamma} \tag{25}$$

Using the value of α_{sd}, we then obtain the equilibrium values of the emissions tax, firm output and abatement:[16]

$$t_{sd} = \frac{A\gamma}{1 + 2\gamma + \sqrt{9 + 4\gamma\,(1 + \gamma)}} \tag{26}$$

$$q_{sd} = \frac{1}{16}A\left[3 + \sqrt{9 + 4\gamma\,(1 + \gamma)} - 2\gamma\right] \tag{27}$$

[16]Given the expressions for equilibrium quantity and abatement, the equilibrium net emissions $e_{sd} = q_{sd} - x_{sd} > 0$.

and

$$x_{sd} = \frac{A}{1 + 2\gamma + \sqrt{9 + 4\gamma(1 + \gamma)}} \quad (28)$$

Finally, equilibrium profit per firm and social welfare can be easily computed by substituting (26),(27) and (28) into (2) and (6).

3 Results

We now compare the equilibrium outcomes under the two different managerial compensation schemes, summarised in the following three propositions.

Proposition 1 *Firm profits are higher under environmental delegation,* $\pi_{ed} > \pi_{sd}$.

Proposition 2 *The optimal emission tax is lower under environmental delegation,* $t_{ed} < t_{sd}$.

Proposition 3 *There exists a critical value* $\tilde{\gamma}$*, such that:*

1. $\alpha_{ed} \lesseqgtr \alpha_{sd}$ *for* $\gamma \gtreqless \tilde{\gamma}$.
2. $x_{ed} \gtreqless x_{sd}$ *as* $\gamma \gtreqless \tilde{\gamma}$
3. $q_{ed} \gtreqless q_{sd}$ *as* $\gamma \gtreqless \tilde{\gamma}$
4. $(e/q)_{ed} \lesseqgtr (e/q)_{sd}$ *as* $\gamma \gtreqless \tilde{\gamma}$
5. $SW_{ed} \gtreqless SW_{sd}$ *as* $\gamma \gtreqless \tilde{\gamma}$

The critical value is $\tilde{\gamma} = 2.735$.

Proposition 1 establishes that profits are higher with environmental delegation; hence owners/shareholders have a clear incentive to provide such an incentive contract: firms will earn higher profits whenever the managerial incentive contract is indexed to the abatement effort of the manager relative to the standard managerial sales contract. This result is important. With environmental delegation, the owner provides the appropriate incentive to direct managerial efforts towards abatement to reduce the emissions tax bill. The higher profits provide a strong *raison d'être* for firm owners to design this form of managerial compensation under an emissions tax regime. Furthermore, from Proposition 2, we find that the optimal emission tax is lower under environmental delegation. This is a direct consequence of the design of the environmental delegation scheme; this is done so as to take environmental concerns explicitly into account. For a given production level, the manager will undertake increased abatement so that, *ceteris paribus*, a lower emission tax is required. The emission tax as the single policy instrument has a multiple role: the regulator uses it to tackle the environmental externality directly and the underproduction market failure indirectly, while the owner by tying the manager's compensation to the tax savings associated with abatement use the tax indirectly to improve profitability. Note that both Propositions 1 and 2 hold irrespective of the difficulty or effectiveness of "green" R&D as captured by the paramater γ. In contrast, the results contained in Proposition 3 depend crucially on γ. In particular, when R&D is difficult ($\gamma \geq \tilde{\gamma}$), owners place less importance on profitability under environmental delegation relative to sales delegation (part 1). As a result, abatement is higher in *ed* and this, coupled with a lower emission tax results in higher output (so that the output distortion is smaller under *ed*). Moreover, emissions per unit of output are smaller, and social welfare higher relative to *sd*, as both profits and consumer surplus are higher. These results are reversed for easy R&D ($\gamma < \tilde{\gamma}$), when the sales delegation contract, which only rewards abatement activities indirectly via the emission tax, performs better. In summary then, the results we obtain suggest that the emissions tax policy together with firms' employment practices in designing managerial incentive contracts can play a complementary role in curbing pollution. An ancillary issue refers to evaluating the critical value $\tilde{\gamma}$ empirically but this is beyond the scope of the present paper.

4 Concluding Remarks

In this paper we have examined two distinct forms of managerial delegation schemes in a Cournot duopoly with pollution: (1) environmental delegation and (2) standard sales delegation. We find that it is in the interest of both owners/principals to design a contract that induces their managers to deviate from profit maximization and account for abatement activities directly instead of sales. We also find that the emission tax is lower in the environmental delegation contract. Moreover, when "green" R&D is relatively difficult, the environmental delegation scheme results in higher abatement, higher output, lower emissions per unit of output and higher social welfare compared to sales delegation.

This approach opens up a number of areas of further research. For example, one could explore alternative environmental targets in the managerial contract. These measurable targets may include environmental performance metrics beyond pollution abatement such as energy intensity and the like. Another possible evaluation method is to compute comparable environmental indices similar to some third-party environmental indices such as the Dow Jones Sustainable Index and peg the managers' performance to achieve these targets relative to the public index. Secondly, one could consider the combination of emissions taxes with R&D subsidies to avoid excessive reliance on emissions taxes to reduce pollution. Lastly, it would be interesting to study how an environmental managerial compensation scheme can be combined with other market-based instruments such as a cap-and-trade system. These are left for future research.

5 Appendix

A Proofs

A.1 Proof of Lemma 1

Proof Part (i): From (9) the first-partial derivative with respect to α_i gives $\frac{\partial t(\alpha_i,\alpha_j)}{\partial \alpha_i} = \frac{3A\alpha_j^2\gamma}{[3(\alpha_i+\alpha_j)+4\alpha_i\alpha_j\gamma]^2} > 0\ for\ i \neq j$. Part (ii): From (10), $\frac{\partial x_i(\alpha_i,\alpha_j)}{\partial \alpha_i} = -\frac{A\alpha_j(3+4\alpha_j\gamma)}{[3(\alpha_i+\alpha_j)+4\alpha_i\alpha_j\gamma]^2} < 0$ and $\frac{\partial x_i(\alpha_i,\alpha_j)}{\partial \alpha_j} = \frac{3A\alpha_i}{[3(\alpha_i+\alpha_j)+4\alpha_i\alpha_j\gamma]^2} > 0$. Part (iii): From (11), $\frac{\partial q_i(\alpha_i,\alpha_j)}{\partial \alpha_i} = -\frac{A\alpha_i^2\gamma}{[3(\alpha_i+\alpha_j)+4\alpha_i\alpha_j\gamma]^2} < 0\ for\ i \neq j$.

A.2 Proof of Propositions 1-3

Proposition 1

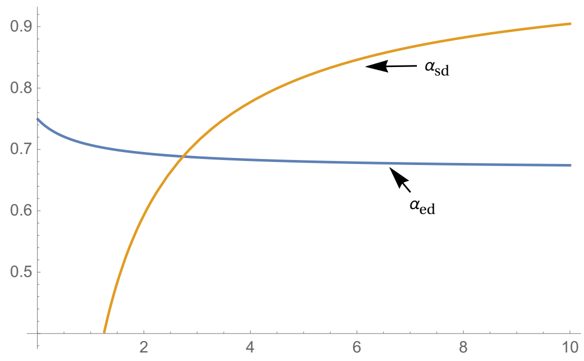
The difference in profits, after some manipulation can be written as
$\pi_{ed}-\pi_{sd} = \frac{A^2\left(8\sqrt{4\gamma^2+10\gamma+4}+2\gamma\left(8\sqrt{4\gamma^2+10\gamma+4}+2\gamma-9\sqrt{4\gamma(\gamma+1)+9}+26\right)-45\sqrt{4\gamma(\gamma+1)+9}+169\right)}{576(2\gamma+5)} > 0$ for all $\gamma > 0$.

Proposition 2

Using expressions (14) and (26), we obtain
$t_{ed} - t_{sd} = \frac{A\left(2\sqrt{4\gamma^2+10\gamma+4}-\gamma(2\gamma+5)\left(-2\gamma+\sqrt{4\gamma(\gamma+1)+9}-1\right)-4\right)}{8(2\gamma+5)} < 0$ for all $\gamma > 0$.

Proposition 3

Using expressions (13) and (25), we obtain
$\alpha_{ed} - \alpha_{sd} = \frac{11+2\sqrt{2(2\gamma+1)(\gamma+2)}-\left[2\gamma+3\sqrt{9+4\gamma(1+\gamma)}\right]}{12\gamma} \gtrless 0$, which results in $\alpha_{ed} \gtrless \alpha_{sd} \Leftrightarrow \gamma \lessgtr 2.735$.



The remaining parts of the proposition are established in a similar manner, using (16),(28),(15),(27) and (6).

$$x_{ed} - x_{sd} = \frac{A\left[43+2\gamma\left(22+6\gamma-3\sqrt{9+4\gamma(1+\gamma)}\right)-\left(4\sqrt{2(2\gamma+1)(\gamma+2)}+15\sqrt{9+4\gamma(1+\gamma)}\right)\right]}{24(5+2\gamma)} \gtreqless 0,$$

or, $x_{ed} \gtreqless x_{sd} \Leftrightarrow \gamma \gtreqless 2.735$.

$$q_{ed} - q_{sd} = \frac{A\left[43+2\gamma\left(22+6\gamma-3\sqrt{9+4\gamma(1+\gamma)}\right)-\left(4\sqrt{2(2\gamma+1)(\gamma+2)}+15\sqrt{9+4\gamma(1+\gamma)}\right)\right]}{48(5+2\gamma)} \gtreqless 0,$$

or, $q_{ed} \gtreqless q_{sd} \Leftrightarrow \gamma \gtreqless 2.735$.

$$(e/q)_{ed} - (e/q)_{sd} = \frac{\gamma\left(2\sqrt{4\gamma^2+10\gamma+4}+6\gamma-5\sqrt{4\gamma(\gamma+1)+9}+27\right)-16\left(\sqrt{4\gamma(\gamma+1)+9}-3\right)}{2\gamma(5\gamma+16)} \lesseqgtr 0$$

or, $(e/q)_{ed} \lesseqgtr (e/q)_{sd} \Leftrightarrow \gamma \gtreqless 2.735$.

$$SW_{ed} - SW_{sd} = \left[\frac{A^2\left(-4\gamma^3+2\left(8\sqrt{4\gamma^2+10\gamma+4}-5\sqrt{4\gamma(\gamma+1)+9}+34\right)\gamma^2+\left(4\sqrt{4\gamma^2+4\gamma+9}\sqrt{4\gamma^2+10\gamma+4}-4\sqrt{4\gamma^2+10\gamma+4}-7\sqrt{4\gamma(\gamma+1)+9}+41\right)\gamma+30\sqrt{4\gamma^2+10\gamma+4}-73\sqrt{4\gamma(\gamma+1)+9}-22\sqrt{(\gamma+2)(2\gamma+1)}\sqrt{8\gamma(\gamma+1)+18}+165\right)}{2\left(\sqrt{4\gamma^2+10\gamma+4}+2\gamma+7\right)^2\left(2\gamma+\sqrt{4\gamma(\gamma+1)+9}+1\right)^2}\right] \gtreqless 0, \tag{29}$$

or, $SW_{ed} \gtreqless SW_{sd} \Leftrightarrow \gamma \gtreqless 2.735$.

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