Environmental delegation versus sales delegation:

a game-theoretic analysis

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ONLINE APPENDIX

The narrative of Section 2.1

In the subgame in which both firms adopt the ed contract or the sd contract, one should start by considering the fourth stage of the game in which the manager hired in firm i maximises his/her utility (equation (4) under ed or equation (5) under sd in the main text) with respect to q_i. This is done by taking as given the incentive parameter in the managerial compensation scheme (α_i), the emission tax rate (t) and the abatement effort (x_i). One can then obtain the output best-response functions, which are independent of the abatement effort (the shape of the R&D abatement technology does not allow interactions with the production, which is a quite standard assumption in this literature), allowing the equilibrium quantity to be obtained as a function of the tax rate.

After this, the third stage comes in which manager i does account for the profit-maximising value of q_i, and then chooses the abatement effort x_i by maximising his/her utility, taking the emission tax rate t as given. At the same time, the regulator (government) – knowing the optimal amount of production computed by managers at the fourth stage – maximises social welfare with respect to t and taking x_i and x_j as given. This process allows us to get a system of best-response functions that can be used to compute the equilibrium values of t, x_i and q_i as a function of the incentive parameters α_i and α_j, that is $t(\alpha_i, \alpha_j)$, $x_i(\alpha_i, \alpha_j)$ and $q_i(\alpha_i, \alpha_j)$.

At the second stage, the owner of firm i – knowing the extent of the variables set at the previous stage – maximises his/her profits and chooses α_i to get the optimal value as a function of α_j. By considering the symmetric counterpart behaviour of the owner of firm j, one can get the system of the incentive parameter best response functions allowing the symmetric optimal value of α^{ed} to be computed under the environmental delegation contract, and α^{sd} under the sales delegation contract. The objective function is concave in q_i and x_i as both variables enter additively (given the shape of the R&D abatement technology). Things would be different if this technology replicated the cost-reducing behaviour (process innovation) following the pioneering contributions of d'Aspremont and Jacquemin (1988, 1990). In addition, the second-order conditions for a maximum (concavity) computed at the second stage are always fulfilled. They are computed, in each subgame, as $\left.\frac{\partial^2 \Pi_i^{ed}(\alpha_i,\alpha_j)}{\partial \alpha_i^2}\right|_{\alpha_i=\alpha^{ed}} < 0$ and $\left.\frac{\partial^2 \Pi_i^{sd}(\alpha_i,\alpha_j)}{\partial \alpha_i^2}\right|_{\alpha_i=\alpha^{sd}} < 0$.

Numerical examples aiming at clarifying the outcomes of Section 3

Let $\gamma = 3$ (efficient abatement technology). Then, $\alpha^{ed} = 0.687$, $\alpha^{sd} = 0.712$, $\alpha_1^{ed/sd} \cong 0.606$ and $\alpha_2^{ed/sd} \cong 0.381$. Profits are $\Pi^{ed} = 0.084$, $\Pi^{sd} = 0.071$, $\Pi_1^{ed/sd} = 0.057$ and $\Pi_2^{ed/sd} = 0.086$. In addition, we have $\Delta\Pi_A(\gamma) < 0$, $\Delta\Pi_B(\gamma) > 0$ and $\Delta\Pi_C(\gamma) < 0$. The payoff matrix the owners face at the first stage of the game can easily be obtained by considering the equilibrium values of profits under the different strategic profiles available to each owner, summarised in table A1.

Table A1. The managerial decision game. Payoff matrix when $\gamma = 3$

	Firm 2	
Firm 1	ed	sd
ed	0.084, 0.084	0.057, 0.086
sd	0.086, 0.057	0.071, 0.071

Clearly, sd is the dominant strategy and (sd,sd) is the unique Pareto inefficient Nash equilibrium of the game, so that the owners are cast into a prisoner's dilemma. They would prefer switching towards the environmental contract; however, the (selfish) maximisation of their own profits leads them to design the standard sales contract. This is because the abatement technology is sufficiently efficient to allow the owners to skip the design of an ad hoc environmentally related, or eco-friendly, managerial contract. Indeed, in this case, the design of the bonus that the owner of the ed firm in the asymmetric subgame would have to pay to his/her manager under the eco-friendly contract would be very high, reducing profits substantially.

Finally, this outcome implies that the society is worse off as social welfare under ed is larger than social welfare under sd, which is the contract emerging in the market, i.e., $SW^{ed} = 0.3 > 0.299 = SW^{sd}$. Given the Nash equilibrium outcome, a Pareto efficient result for society cannot be achieved even for $1.83 < \gamma < 2.735$. This is because, though $SW^{ed} < SW^{sd}$ holds in this case, the prisoner's dilemma firms are entrapped which implies that they would be better off under ed.

Let $\gamma = 15$ (inefficient abatement technology). Then, $\alpha^{ed} = 0.67$, $\alpha^{sd} = 0.93$, $\alpha_1^{ed/sd} \cong 0.65$ and $\alpha_2^{ed/sd} \cong 0.85$. Profits are given by $\Pi^{ed} = 0.0692$, $\Pi^{sd} = 0.064$, $\Pi_1^{ed/sd} = 0.06$ and $\Pi_2^{ed/sd} = 0.0691$. In addition, we have $\Delta\Pi_A(\gamma) < 0$, $\Delta\Pi_B(\gamma) < 0$ and $\Delta\Pi_C(\gamma) < 0$. The payoff matrix the owners face at the first stage of the game can easily be obtained by considering the equilibrium values of profits under the different strategic profiles available to each owner, summarised in table A2. Clearly, there is no dominant strategy, and multiple Nash equilibria arise in pure strategies, i.e., (sd,sd) and (ed,ed), leading to a coordination game. This is because the abatement technology is sufficiently inefficient to allow the owners to make potentially convenient the design of an ad hoc environmentally-related or eco-friendly managerial contract. Indeed, in this case: 1) the design of the bonus that the owner of the ed firm in the asymmetric subgame would have to pay to his/her manager under the eco-friendly contract is lower than the one that should be designed by the owner of the sd firm, and this contributes to an increase in the relative profits of the ed firm; and 2) the bonus paid when both owners design the ed contract is the second lowest possible. We note that, if the owners were able to coordinate their strategies unilaterally towards the ed contract in this noncooperative game, the society would be better off, resulting in a Pareto efficient outcome, i.e., $SW^{ed} = 0.264 > 0.261 = SW^{sd}$.

The numerical examples above reveal that a reduction in γ (i.e., an increase in the R&D abatement efficiency) contributes to increased profits in all scenarios (by increasing production and abatement) except for the ed firm in the asymmetric subgame. However, the increase in profits the sd firm obtains when the rival plays ed is such that each firm (owner) has a unilateral incentive to play sd when the rival plays ed; thus, sd becomes a dominant strategy compared to when the value of γ was higher. This occurs because, ceteris paribus, the increase in abatement efficiency reduces the tax savings on which the delegation is based in the ed firm when the rival plays sd; this, in turn, generates a reduction in the incentive parameter designed by the owner to remunerate the green manager (which determines his/her remuneration). In fact, the equilibrium abatement of the ed firm in the asymmetric subgame increases; however, the corresponding output decreases, thus generating a reduction in the optimal taxation. In addition, managers are more aggressive under the ed contract, and they abate more than under the sd contract in the symmetric scenarios, and this contributes to increased profits for the ed firm.

Table A2. The managerial decision game. Payoff matrix when $\gamma = 15$

	Firm 2	
Firm 1	ed	sd
ed	0.0692, 0.0692	0.06, 0.0691
sd	0.0691, 0.06	0.064, 0.064

References

d'Aspremont C and Jacquemin A (1988) Cooperative and noncooperative R&D in duopoly with spillovers. *American Economic Review* **78**(5), 1133–1137.

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