Discussion Papers

Adhibe rationem difficultatibus

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Green" managerial delegation theory

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Abstract

Is it profitable to include an environmental ("green") incentive in a managerial contract when a dirty technology causes pollution externality, and the government levies an emissions tax? This research considers a non-cooperative Cournot duopoly game in which owners choose whether to delegate output and the abatement choices to their managers to address the above question. When the societal (or public) evaluation of the environmental damage is sufficiently low, two symmetric equilibria emerge (both firms are either "green" or "polluting"); when the public environmental concern becomes larger, the "green" delegation is the unique Nash equilibrium, which is Pareto inefficient (resp. efficient) for intermediate (resp. high) values of the government's weight towards the environment. Differently, in a managerial duopoly where owners delegate only sales or sales and abatement, sales delegation arises in equilibrium; however, firms face a Prisoner's Dilemma because "green" delegation yields higher profits.

Keywords   "Green" managerial delegation; Abatement; Emissions tax; Cournot duopoly

JEL Classification   H23, L1, M5, Q58

1. Introduction

According to a report issued by KPMG (2017), a large majority (67 percent) of the firms belonging to the G250 Fortune Index (a list of the largest 250 multinationals) has revealed targets to cut carbon emissions.[1] All those companies are defined by the separation between ownership and control, which is delegated to managers. However, only a minority (25 percent) of them links their own targets to the climate goals that have being fixed by national governments, regional authorities, or the United Nations, such as The Paris Agreement.

On the other hand, family firms constitute another pillar in the economic activity of several European, Asian, and Latin American countries (see García-Ramos and García-Olalla, 2011; Chrisman et al., 2014; Singal and Gerde, 2015). In those companies, the family group has a central influence on the ownership, governance, management, and the company's objectives and strategies. Irrespective of their nature of public listed/privately held companies, empirical works have highlighted that family firms widely report environmental disclosure, and may focus more or less on environmental performance than non-family business (Berrone et al. 2010; Dekker and Hasso, 2016; Arena and Michelon, 2018; Zhu and Lu, 2020). This suggests that there is room for intervention to readjust the firms' targets with those of environmentally responsive social planners.

At this point, some questions arise: in strategic settings such us oligopolistic (duopolistic) markets, is it always advantageous for the owners of a firm to include an environmental friendly incentive within a "green" managerial scheme when the existing dirty technology cause pollution externalities and a government levies an emissions tax? Should owners retain for them the decision on how much emissions to abate or leave it to a manager (under an

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[1] On September 10th 2020, Mike Henry, chief executive of the BHP Group (the world's biggest listed miner) announced that the company will focus on cutting its operational emissions by 30% by the 2030 financial year from 2020 levels, and will link executive bonuses to its progress. For the sake of precision, BHP was included in the G250 Fortune Index from 2005 to 2016, while currently ranks #261in the G500 Fortune Index.

appropriate incentive scheme)? Indeed, what is the best option for firms' owners, to offer a "green" delegation contract or a standard sales delegation one? This contribution focuses precisely on these points. Given the growing worldwide apprehension in the public opinion due to the demand for immediate need to reduce the emission of greenhouse gases launched by climate scientists because of future potential impacts on global, local political as well as economic systems (see "The climate issue", The Economist, 2019), such an investigation appears to be well-timed, and surprisingly missing in the related literature.

The present work, therefore, considers a Cournot duopoly where dirty technologies generate pollution externalities and studies the owners' decision whether to delegate the choice of the abatement level in the presence of a government that levies an emissions tax. The key results of the work are as follows. Making use of a four-stage non-cooperative game in which, first, the government sets the emission tax, and then owners choose whether to retain the choices of the abatement and output levels or delegate them to a manager via a "green" or "sales" delegation contract choosing the related incentive, a rich set of game equilibria emerges depending on the relative weight of the public evaluation of the environmental damage. In details, when the public awareness towards the environmental damage is sufficiently low, two symmetric equilibria emerge: owners can either retain the strategic choices or delegate them through "green" compensation schemes. Nonetheless, the profits with the standard profit maximization rule payoff-dominate those with the "green" delegation contract. When the public awareness towards the environmental damage becomes higher, "green" delegation becomes the dominant strategy, but firms face a Prisoner's Dilemma. On one hand, the work also compares these results with the classical sales managerial delegation game augmented with pollution abatement: the standard result in which managerial delegation arises as a Prisoner's Dilemma is confirmed. On the other hand, in a four stage game in which, first, the government levies the emission tax, second, owners

choose whether to offer a standard sales delegation contract or a "green" delegation contract and the relative incentive bonus to managers, and then managers take the relevant decisions, it is shown that owners, in equilibrium, offer the former contract; however, they face a Prisoner's Dilemma as profits generated by the "green" contract are higher, therefore having an unilateral incentive for "green delegation".

The remainder of the paper is organised as follows. Section 2 reviews the related literature. Section 3 describes the model and discusses the main results. Section 4 briefly presents the social welfare consequences of the firms' strategic behaviour. Section 5 extends the model with horizontal product differentiation for robustness check. Section 6 closes the paper with an outline of the next research agenda.

2. Literature review

This work links to a broad corpus of the literature in economics focusing on environmental questions. The first contributions have made use of simple frameworks in which each firm produces homogenous goods at a single production plant (see, amongst others, Simpson, 1995; Katsoulacos and Xepapadeas, 1995; Carlsson, 2000). Then, the literature has further developed the analysis to different market configurations. A first line of investigation in this regard studied the strategic environmental policy in an international framework, by investigating how countries strategically act when government levy environmental taxes, unilaterally or cooperatively. A ground-breaking contribution in this direction is Ulph (1996), who considered the strategic environmental policy in countries involved in international trade and whose markets are characterised by imperfect competition. The impact of environmental taxes' coordination on market competition and social welfare is the subject of study in other works such as, for instance, Conrad (1993), Kennedy (1994), Conrad (1996a), Conrad (1996b), Bárcena-Ruiz and Campo (2012), and Bárcena-Ruiz and Garzón (2014). Conrad

(1993) used a third-market model to show that countries set higher environmental taxes when they do not cooperate than when they do. Kennedy (1994) and Conrad (1996a) investigated this issue by assuming home and foreign segmented markets with cross-border pollution. Conrad (1996b) and Bárcena-Ruiz and Campo (2012) extended the latter analysis to Bertrand competition and cross-ownership of firms, respectively. Finally, Bárcena-Ruiz and Garzón (2014) studied the coordination of environmental taxes in the presence of a supranational body and multiproduct firms. A second line of study is the strategic interaction between environmental policy and endogenous location of polluting firms (e.g., Rauscher, 1995; Markusen *et al.*, 1993; Markusen, 1997; Bárcena-Ruiz and Garzón, 2003). For example, Markusen *et al.* (1993) discussed the issue of environmental taxation in a two-market, two-firm model in which firms endogenously establish their plants and showed that the social cost of taxation can be extremely high if market endogeneity is disregarded. Another branch of the literature investigates the link between environmental policies and market structures. The pioneering contributions of Lee (1975) and Smith (1976) revealed that market structures have a relevant impact on the efficiency of environmental taxation. Subsequently, Oates and Strassmann (1984) examined the efficiency of environmental taxation in a mixed market (in which private and public firms operate). Conrad and Wang (1993) analysed pollution taxes and abatement subsidies in three different market structures: perfect competition, oligopoly and a dominant firm with a fringe. Lee (1999) revisited environmental taxation under an endogenous oligopolistic market structure. Althammer and Bucholz (1999) considered the effects of market structures on the (second-best) choice of the environmental tax. Under an endogenous market structure, Katsoulacos and Xepapadeas (1996) found that the optimal emissions tax can exceed the marginal environmental damage. Finally, Cato (2010) studied a three-part environmental tax policy in an endogenous market structure.

Another strand of research also investigates the relationship between vertical structures in an industry (e.g. supply chains) and environmental taxes. In this regard, Gunasekaran *et al.* (2015) reviewed the works with environmental policies and "green" supply chains. Making use of an asymmetric Nash bargaining game, Sheu (2011) examined the impact of governments' financial intervention on cooperative negotiations between manufacturers and reverse-logistics suppliers. Park *et al.* (2015) discussed whether and how carbon fees impact on the supply chain structure and social welfare. Hafezalkotob (2017) developed a model of competition and cooperation between two green supply chains, with an environmental tariff mechanism. Bian *et al.* (2017) examined environmental taxation with vertical market structures in supply chains, inquiring whether the manufacturers vertically integrate or decentralize under endogenous environmental taxation.

Other works analysed and extended the basic framework of oligopolistic rivalry, by assuming either unionised oligopolies (Bárcena-Ruiz, 2011; Bárcena-Ruiz and Garzón, 2003; 2009), or (as our paper does) the separation between ownership and control by introducing managerial delegation contracts. About managerial delegation, the pioneering work of Bárcena-Ruiz and Garzón (2002) studied the strategic effects of delegating to managers sales and pollution abatement in presence of environmental tax and damage by considering a competitive labour market and homogeneous products. Bárcena-Ruiz and Garzón (2003) also studied a managerial delegation model in a framework in which the government sets an environmental tax to control environmental damage. The authors showed that, by offering managers a standard incentive scheme based on a linear combination of profits and sales revenue, on one hand, firms' owners get profits lower than under standard profit-maximisation; on the other hand, they have to pay a higher environmental tax, and both the environmental damage and social welfare with managerial delegation increase. Subsequently, Pal (2012) extended the work of Bárcena-Ruiz and Garzón (2002) by examining how

strategic managerial delegation, product differentiation and alternative modes of market (price and quantity) competition have an impact on optimal emission tax rate, environmental damage and social welfare. The author showed that, under the standard profit maximisation rule, the optimal emission tax does not inevitably decrease in the degree of differentiation among products. Moreover, if managers receive a standard remuneration scheme consisting of a linear combination of profits and sales revenues, the impacts of delegation on the scope for the optimal emission tax to be lower for higher degree of product differentiation are significantly different under alternative modes of competition. Under price (resp. quantity) competition, profits in the case of managerial delegation are higher (resp. lower) than without delegation, but the opposite holds true for equilibrium emission tax rate, environmental damage and social welfare.

There also exists a recent line of research that considered the idea of "green" managerial delegation, that is the introduction of an environmental incentive into the managerial compensation scheme. Indeed, Lee and Park (2019) were the first authors that include an explicit environmental incentive into a managerial compensation contract, representing a form of environmental corporate social responsibility (ECSR). In a sequential price competition game, the authors study the strategic choice of adopting ECSR by polluting firms. The measure of ECSR is given by an internal emission price on the damage produced by the firm, and it is established by the firms' owners. The managerial compensation structure is a linear combination of profits and the ECSR incentive. In such a context, the main result is that when firms sequentially adopt ECSR, they do it to soften competition when the goods are close substitute; nonetheless, the late adopter selects a lower level of ECSR than the early one, and thus earns higher profit. In a Cournot duopoly with pollution externalities and emissions taxes, Poyako-Theotoky and Yong (2019) also introduced an explicit environmental incentive into the compensation scheme owners offer their managers. The authors showed that,

depending on the efficiency level of the "green" research and development activity, the "green" delegation contract yields more abatement levels than the standard sales delegation contract. Consequently, the regulator fixes a lower emissions tax, and social welfare increases. In addition, firm owners earn higher profits when adopting the "green" delegation contract. However, despite the different aspects and contexts studied, none of these contributions has enclosed into the analysis the firms' endogenous choice whether to adopt an abatement technology in presence of an environmental tax as the present paper does.

3. The model and the main results

Consider a duopoly industry in which Firm 1 and Firm 2 compete à la Cournot. Firms produce homogeneous goods and each unit of output causes k units of pollutant. Firms exhibit an identical, constant return to scale technology with linear, constant marginal costs, c which can be set, without loss of generality, equal to zero. There exists a cleaning technology that, however, cannot entirely eliminate the pollutant's emissions (Asproudis and Gil-Moltó, 2015), that is $k_i < q_i$, $i = 1, 2$. Regarding the abatement cost, the pollution abatement function is $CA = \dfrac{zk_i^2}{2}$, where $z > 0$ is a parameter that can be interpreted as an exogenous technical progress index measuring, for example, the arrival of a new, cost-effective technology. The cleaner technology shows decreasing returns to investment (Asproudis and Gil-Moltó, 2015; Ulph, 1996). A reduction (resp. an increase) in k implies a more (resp. less) efficient abatement technology: an equal level of polluting emission can be abated in a cheaper (more expensive) way. Parameter z simply scales up/down the total abatement cost thus representing a measure of the abatement technology's efficiency; however, for easiness and clarity of exposition it can be set equal to one without loss of

Stage 1: Government stage — Government chooses optimal emission tax

Stage 2: Contract stage:
- "Green" delegation game with emission tax
- Sales delegation game with emission tax
- "Green" vs Sales delegation game with emission tax

Stage 3: Bonus stage:
- "Green" delegation: owners choose the executive remuneration, linked to output and emission abatement
- Sales delegation: owners choose the executive remuneration, linked to output
- "Green" delegation: owners choose the executive remuneration, linked to output and emission abatement
- Sales delegation: owners choose the executive remuneration, linked to output

Stage 4: Market stage:
- Managers choose output and abatement levels
- No delegation: owners choose output and abatement levels
- Managers choose output and abatement levels
- No delegation: owners choose output and abatement levels
- Managers choose output and abatement levels
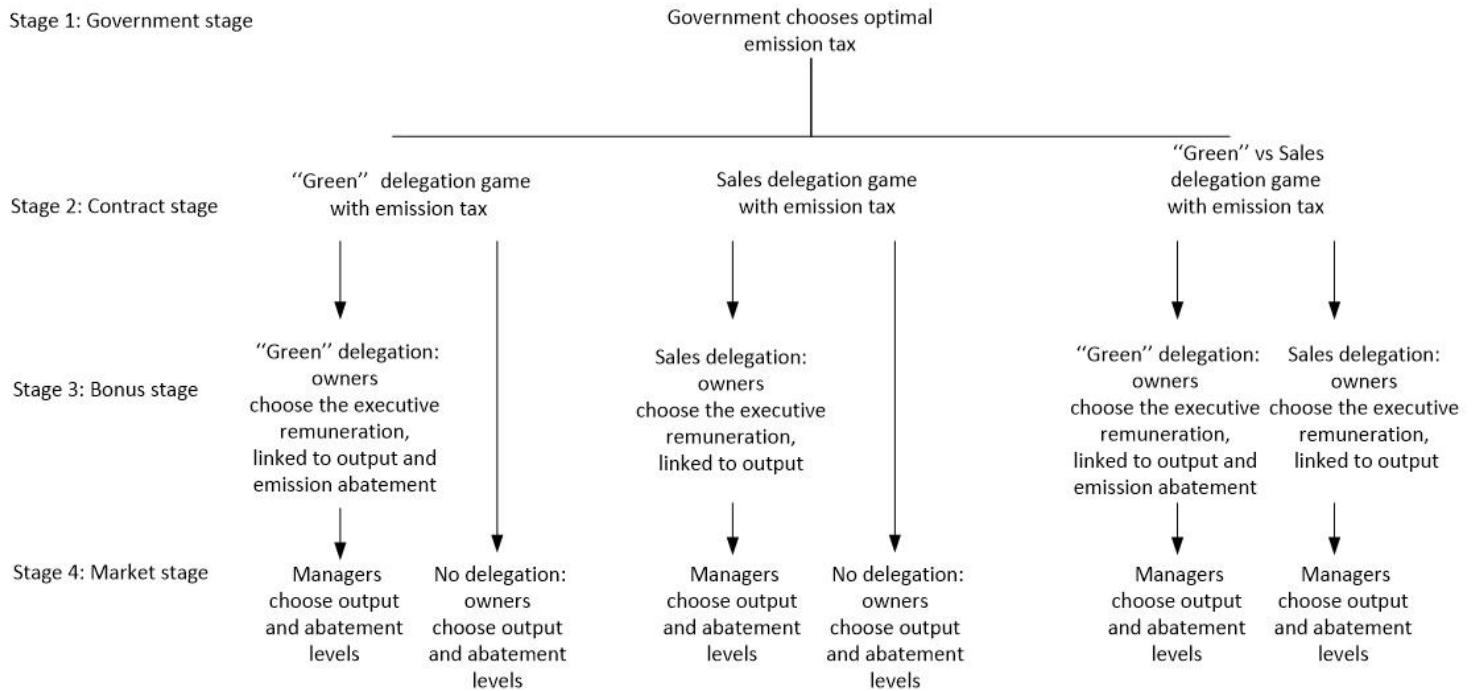- Managers choose output and abatement levels

Figure 1: Timing of the game.

generality.[2] The government levies an emissions tax, $t \in (0,1]$ per each unit of polluting output. The generic abating firm i faces the tax base $q_i - k_i$ (pollution) and the corresponding tax revenue therefore is $t(q_i - k_i)$.

The game has a four-stage structure, as depicted in Figure 1. At stage one, the government chooses the optimal emission tax to maximise social welfare (*the government stage*). At the stage two, owners compare the nature of the bonuses (*the contract stage*) by choosing to be delegated or profit maximising. At stage three, owners choose the executive remuneration (*the bonus stage*). At stage four (*the market stage*), if owners retain the abatement decision, they simultaneously choose the optimal levels of output and abatement. Otherwise, owners can delegate to managers abatement and sales decisions.

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[2] This assumption can be retained because the second order conditions of the maximization problem are always satisfied for any $z > 0$.

3.1 "Green" delegation game with emission tax

3.1.1 Owners decide the quantity and abatement levels

Consider first the case in which the decision about the level of abatement is taken by the owner of each firm. Therefore, the profit function of firm i is the following:

$$\pi_i^{PM} = (1 - q_i - q_j)q_i - t(q_i - k_i) - \frac{k_i^2}{2}, \ i = 1, 2; \ i \neq j, \tag{1}$$

where the superscript *PM* stands for profit-maximisation. In the last stage of the game, owners choose both the optimal output and abatement levels. Maximization of (1) with respect to q_i and k_i yields the following set of first order conditions:

$$A) \ q_i = \frac{(1 - q_j - t)}{2}; \ B) \ k_i = t \ , \ i = 1, 2; \ i \neq j. \tag{2}$$

The solution of the system of output reaction functions A) in (2) leads to the following equilibrium output:

$$q_i = \frac{(1 - t)}{3}. \tag{3}$$

Using (3) and condition B) in (2), one can directly obtain the next expressions for the producer surplus, consumer surplus, tax revenues and environmental damage:

$$PS^{PM} = (\pi_1^{PM} + \pi_2^{PM}) = \frac{1}{9}(2 - 4t + 11t^2), \tag{4}$$

$$CS^{PM} = \frac{(q_1 + q_2)^2}{2} = \frac{2}{9}(1 - t)^2, \tag{5}$$

$$TR^{PM} = t[(q_1 - k_1) + (q_2 - k_2)] = \frac{2}{3}t(1 - 4t), \tag{6}$$

$$ED^{PM} = g(q_1 - k_1)^2 + g(q_2 - k_2)^2 = \frac{g}{3}(1 - 4t)^2. \tag{7}$$

The expression of the social welfare ($SW = PS + CS + TR - ED$) under PM is the following:

$$SW^{PM} = \frac{1}{9}[4 - g + (8g - 2)t - (16g + 11)t^2].$$ (8)

In the first stage, the government levies an emission tax with the aim of maximising social welfare, and the welfare maximising tax rate is obtained follows:

$$\frac{\partial SW^{PM}}{\partial t} = 0 \Rightarrow t^{*PM} = \frac{4g - 1}{16g + 11}.$$ (9)

From Eq. (9), $t^{*PM} > 0$ if and only if $g > \frac{1}{4}$. Using the optimal tax in (9), one can check that

$q_i^{PM} > 0$, $k_i^{PM} > 0$ if $g > \frac{1}{4}$, and that $q_i^{PM} > k_i^{PM}$ is always fulfilled. Finally, inserting back

the optimal tax t^{*PM} into the equilibrium profit function one gets:

$$\pi_1^{*PM} = \pi_2^{*PM} = \frac{48g^2 + 56g + 33}{2(11 + 16g)^2}.$$ (10)

3.1.2 Owners delegate both the quantity and abatement levels to managers ("green" delegation)

Let us now consider the case in which owners delegate the output decision and the abatement level to their own managers ("green" delegation). In a managerial delegation model, each firm consists of owners who control the firm and a manager whose decisions are based on an incentive contract that the corresponding owner designs. Managers get a public observed contract whose remuneration is $R_i = A + BU_i \geq 0$, where $A \geq 0$ is the fixed salary component of the manager's compensation, $B \geq 0$ is a constant parameter, and U_i is the manager i's utility. Without loss of generality, the fixed salary component A is set equal to zero and B equal to one. Each manager's compensation structure is proportional to a linear combination of profit and the "green" incentive. The payoff function of the manager of the polluting firm i takes a form similar to Vickers (1985), Sklivas (1987), and Fershtman and Judd (1987), that is:

$$U_i^{GD} = \pi_i + b_i(q_i - k_i), \ i = 1, 2,$$ (11)

where the superscript GD stands for "green" delegation, π_i are profits in (1) and b_i is the owners' incentive (disincentive) regarding quantity and abatement chosen by the manager, which determine the pollution level, $q_i - k_i$. Therefore, from the maximisation of the managers' utility function in (11) with respect to q_i and k_i, we get the following first order conditions (FOCs):

A) $q_i = \dfrac{1}{2}(1 - q_j - t + b_i)$; B) $k_i = t - b_i$, $i = 1, 2; \ i \neq j$. (12)

The solution of the system of output reaction functions A) in (12) gives the following equilibrium output as a function of the bonuses:

$$q_i = \frac{1}{3}(1 - t + 2b_i - b_j), \ i = 1, 2; \ i \neq j,$$ (13)

Substituting (13) and condition B) in (12) into (1) one obtains the expression of the firms' profits as a function of the managerial incentives; firm i's owners maximize profits with respect to the bonus b_i which leads to the following reaction functions in the bonus space:

$$b_i = \frac{1}{13}(1 - t - b_j), \ i = 1, 2; \ i \neq j$$

Therefore, in equilibrium, one gets:

$$b_i^{GD} = b_j^{GD} = \frac{1 - t}{14} \text{ and } k_i^{GD} = k_j^{GD} = \frac{15t - 1}{14}.$$ (14)

Making use of (14), further substitutions directly yield the expressions for the producer surplus, consumer surplus, tax revenues and environmental damage under GD, that is:

$$PS^{GD} = (\pi_1^{GD} + \pi_2^{GD}) = \frac{1}{196}(39 - 28t + 235t^2),$$ (15)

$$CS^{GD} = \frac{(q_1 + q_2)^2}{2} = \frac{5}{98}(1 - t)^2,$$ (16)

$$TR^{GD} = t[(q_1 - k_1) + (q_2 - k_2)] = \frac{2}{7}t(3 - 10t), \tag{17}$$

$$ED^{GD} = g(q_1 - k_1)^2 + g(q_2 - k_2)^2 = \frac{g}{49}(3 - 10t)^2. \tag{18}$$

The expression of the social welfare is

$$SW^{GD} = \frac{1}{196}[89 - 36g + (240g - 10)t - (400g + 275)t^2]. \tag{19}$$

In the first stage, the government sets the emission tax to maximise social welfare, that is:

$$\frac{\partial SW^{GD}}{\partial t} = 0 \Rightarrow t^{*GD} = \frac{24g - 1}{80g + 55}. \tag{20}$$

From Eq. (20), $t^{*GD} > 0$ if and only if $g > \frac{1}{24}$. Using the optimal tax in (20), one can verify

that $q_i^{GD} > 0$, $k_i^{GD} > 0$ if $g > \frac{1}{24}$, and that $q_i^{GD} > k_i^{GD}$ is always fulfilled. Finally, inserting

back the optimal tax t^{*GD} into the equilibrium profit function one gets:

$$\pi_1^{*GD} = \pi_2^{*GD} = \frac{48g^2 + 48g + 25}{2(11 + 16g)^2}. \tag{21}$$

3.1.3 Mixed case: only the owner of one firm delegates via a "green" contract

To determine the owners' endogenous choice whether to delegate via a "green" contract, one

should evaluate the outcomes of the asymmetric game in which one firm, say Firm 1,

"green"-delegates while the rival, Firm 2, is still profit maximising. The two optimisation

problems lead to the first order conditions as in (12) for Firm 1 and as in (2) for Firm 2.

Solving the system of the output reaction functions, one obtains:

$$q_1 = \frac{1}{3}(1 - t + 2b_1) \text{ and } q_2 = \frac{1}{3}(1 - t - b_1). \tag{22}$$

Substituting (22) and condition B) in (12) into the profit function of Firm 1, one gets the

expression of Firm 1's profits as a function of the managerial incentive. Thus, the owner of

Firm 1 maximises profits with respect to b_1. This gives the optimal bonus $b_1 = \frac{1}{13}(1-t)$ and therefore, in equilibrium

$$q_1^{GD/PM} = \frac{5}{13}(1-t), \quad q_2^{GD/PM} = \frac{4}{13}(1-t), \text{ and } k_i^{GD/PM} = \frac{1}{13}(14t-1), \quad k_2^{GD/PM} = t. \tag{23}$$

Making use of (23), direct substitutions lead to the expressions for the producer surplus, consumer surplus, tax revenues and environmental damage in the asymmetric case, that is:

$$PS^{GD/PM} = (\pi_1^{GD/PM} + \pi_2^{GD/PM}) = \frac{1}{338}(71 - 142t + 409t^2), \tag{24}$$

$$CS^{GD/PM} = \frac{(q_1+q_2)^2}{2} = \frac{81}{338}(1-t)^2, \tag{25}$$

$$TR^{GD/PM} = t[(q_1-k_1)+(q_2-k_2)] = \frac{2}{13}t(5-18t), \tag{26}$$

$$ED^{GD/PM} = g(q_1-k_1)^2 + g(q_2-k_2)^2 = \frac{g}{13}(25t^2 - 14t + 2). \tag{27}$$

The social welfare is given by

$$SW^{GD/PM} = \frac{1}{169}[76 - 26g + (182g - 22)t - (325g + 223)t^2]. \tag{28}$$

Therefore, in the first stage of the game, the government chooses the emission tax such that the social welfare in (28) is maximised, that is:

$$\frac{\partial SW^{GD/PM}}{\partial t} = 0 \Rightarrow t^{*GD/PM} = \frac{91g-11}{325g+223}. \tag{29}$$

From Eq. (29), $t^{*GD/PM} > 0$ if and only if $g > \frac{11}{91}$. Using the optimal tax in (29) and taking into account the constraint $g > \frac{11}{91}$, one gets $q_i^{GD/PM} > 0$, but $k_1^{GD/PM} > 0$ if and only if $g > \frac{29}{73}$, and that $q_i^{GD/PM} > k_i^{GD/PM}$ is fulfilled only when $\frac{29}{73} < g < \frac{83}{19}$. Finally, by using the optimal tax in (29), equilibrium profits in the asymmetric case are the following:

$$\pi_1^{*GD/PM} = \frac{20917g^2 + 23270g + 12757}{2(223 + 325g)^2} ; \quad \pi_2^{*GD/PM} = \frac{18649g^2 + 18734g + 10489}{2(223 + 325g)^2} . \qquad (30)$$

3.1.4 The owners' endogenous choice: the "green" delegation game

Using the firms' profits in (10), (21) and (30), one can get the payoff matrix reported in Table 1 about the "green" delegation game. To satisfy the technical restrictions and obtain well-identified equilibria in pure strategies for all strategic profiles, the analysis is confined to the following range of the environmental damage, $\frac{29}{73} < g < \frac{83}{19}$.

Table 1: The "green" delegation game (payoff matrix)

Firm 1; Firm 2→ ↓	GD	PM
GD	$\pi_1^{*GD} = \frac{48g^2 + 48g + 25}{2(11 + 16g)^2} ; \pi_2^{*GD} = \frac{48g^2 + 48g + 25}{2(11 + 16g)^2}$	$\pi_1^{*GD/PM} = \frac{18649g^2 + 18734g + 10489}{2(223 + 325g)^2} ;$ $\pi_2^{*GD/PM} = \frac{20917g^2 + 23270g + 12757}{2(223 + 325g)^2}$
PM	$\pi_1^{*PM/GD} = \frac{20917g^2 + 23270g + 12757}{2(223 + 325g)^2} ;$ $\pi_2^{*PM/GD} = \frac{18649g^2 + 18734g + 10489}{2(223 + 325g)^2}$	$\pi_1^{*PM} = \frac{48g^2 + 56g + 33}{2(11 + 16g)^2} ; \pi_2^{*PM} = \frac{48g^2 + 56g + 33}{2(11 + 16g)^2}$

To derive all the game equilibria, it is important to study the sign of the following set of profit differentials:

$$\Delta\pi_1 = \pi_i^{GD/PM} - \pi_i^{PM} ; \quad \Delta\pi_2 = \pi_i^{PM/GD} - \pi_i^{GD} \quad \Delta\pi_3 = \pi_i^{PM} - \pi_i^{GD} \text{ for } i = 1, 2 \qquad (31)$$

An analytical inspection of the expressions in (31) reveals that

$$\Delta\pi_1 \underset{>}{\overset{<}{=}} 0 \quad if \quad g \underset{>}{\overset{<}{=}} 0.766 ; \Delta\pi_2 < 0 ; \Delta\pi_3 > 0 ,$$

from which one can get the following result.

Result 1. *When the government levies an emission tax with the aim of maximising social welfare, the "green" delegation game generates the following Nash equilibria:*

i) *If* $g \in (0.397, 0.766)$*, there are two symmetric equilibria, (GD,GD) and (PM,PM) but PM Pareto dominates GD.*

ii) *If* $g \in [0.766, 4.368)$*, GD becomes the dominant strategy. Therefore, (GD,GD) is the Nash equilibrium, but it is Pareto-dominated by (PM,PM): firms are cast into a Prisoner's Dilemma.*

When the public evaluation of the environmental damage is low, there exist multiple Nash equilibria in pure strategies, and owners may find it profitable to retain the strategic decisions for themselves rather than delegate them to a manager. In fact, on one hand, via delegation, the owners instruct managers to expand output, thus increasing pollution. This implies that the emission tax in presence of universal "green" delegation is higher than without delegation. On the other hand, managers have an incentive to reduce pollution, allowing the firm to save on taxation; nonetheless, the tax differential under the two contexts is sufficiently high that the firms' owners can save more on taxation by retaining the abatement level decisions. As the government's evaluation of the environmental damage increases, "green" delegation emerges from the strategic interaction in the product market as the dominant strategy for the owners. The emission tax rate increases and, therefore, the impact of environmental taxes on firms' profits is much larger than when the tax rate is low. Moreover, in the asymmetric context, because of the combined effect of output expansion and lower taxes, the owners have a unilateral incentive to "green" delegate as profits are larger.

3.2 Standard sales delegation game with emission tax

Now, we study a standard sales delegation game in the presence of emission tax when firms have invested in abatement technologies. The case in which both owners do not delegate is precisely as in subsection 3.1.1. Therefore, we can concentrate on the universal adoption of sales delegation and the asymmetric case in which only one firm becomes delegated.

3.2.1 Owners offer a contract based on output (sales delegation)

Consider the case in which owners offer a standard output (sales) delegation contract to a manager who must choose both output and abatement levels. The payoff function of the manager now takes the form as in Vickers (1985), Sklivas (1987), and Fershtman and Judd (1987):

$$U_i^{SD} = \pi_i + b_i q_i, \ i = 1, 2, \tag{32}$$

where the superscript *SD* stands for sales delegation, π_i are profits in (1) and b_i is the owners' incentive (disincentive) about the output level chosen by the manager. From the maximisation of the managers' utility function in (32) with respect to q_i and k_i, the FOC's are the following:

A) $q_i = \dfrac{1}{2}(1 - q_j - t + b_i)$; B) $k_i = t$, $i = 1, 2$; $i \neq j$. $\tag{33}$

Solving the system of output reaction functions A) in (33), one gets the solution as in (13). Substituting (13) and condition B) in (33) into (1), one obtains the firms' profits as a function of the managerial bonuses; firm i's owners maximise profits with respect to b_i which yields the reaction functions in the bonus space $b_i = \dfrac{1}{4}(1 - t - b_j)$ and thus, in equilibrium

$$b_i^{SD} = b_j^{SD} = \frac{1}{5}(1 - t) \text{ and } k_i^{SD} = k_j^{SD} = t. \tag{34}$$

Using (34), subsequent substitutions lead to the expressions of the producer surplus, consumer surplus, tax revenues and environmental damage:

$$PS^{SD} = (\pi_1^{SD} + \pi_2^{SD}) = \frac{4}{25}(1 - 2t + 29t^2),$$ (35)

$$CS^{SD} = \frac{(q_1 + q_2)^2}{2} = \frac{8}{25}(1 - t)^2,$$ (36)

$$TR^{SD} = t[(q_1 - k_1) + (q_2 - k_2)] = \frac{2}{5}t(2 - 7t),$$ (37)

$$ED^{SD} = g(q_1 - k_1)^2 + g(q_2 - k_2)^2 = \frac{g}{25}(2 - 7t)^2.$$ (38)

The social welfare is

$$SW^{SD} = \frac{1}{25}[12 - 4g + (28g - 4)t - (49g + 33)t^2].$$ (39)

In the first stage, the government chooses the optimal emission tax by maximising Eq. (39), that is:

$$\frac{\partial SW^{SD}}{\partial t} = 0 \Rightarrow t^{*SD} = \frac{2(7g - 1)}{49g + 33}.$$ (40)

From Eq. (40), $t^{*SD} > 0$ if and only if $g > \frac{1}{7}$. Given the optimal tax in (40), one can check that the condition $q_i^{SD} > 0$ is always satisfied, $k_i^{SD} > 0$ if $g > \frac{1}{7}$, and $q_i^{SD} > k_i^{SD}$ is always fulfilled. Finally, making use of the optimal tax in (40), the equilibrium profits are under SD are the following:

$$\pi_1^{*SD} = \pi_2^{*SD} = \frac{4(49g^2 + 42g + 25)}{(49g + 33)^2}.$$ (41)

3.2.2 Mixed case: only the owners of one firm delegate via a sales delegation contract

To derive the owners' endogenous choice whether to delegate, one must compute the outcomes of the asymmetric game in which one firm, say Firm 1, delegates while the rival, Firm 2, does not. The two optimisation problems lead to first order conditions as in (33) for Firm 1 and as in (2) for Firm 2. Solving the system of the output reaction functions, one obtains the output levels as in (22). Substituting these outcomes along with condition B) in (33) into the profit function of Firm 1, one gets the expression of Firm 1's profits as a function of the managerial incentive. It follows that Firm 1's owners maximise profits with respect to b_1, leading to the optimal bonus $b_1 = \frac{1}{4}(1-t)$. Therefore, equilibrium outcomes are the following:

$$q_1^{SD/PM} = \frac{1}{2}(1-t), \ q_2^{SD/PM} = \frac{1}{4}(1-t) \text{ and } k_1^{SD/PM} = k_2^{SD/PM} = t. \tag{42}$$

Making use of (42), direct substitutions lead to the producer surplus, consumer surplus, tax revenues and environmental damage in this asymmetric case:

$$PS^{SD/PM} = (\pi_1^{SD/PM} + \pi_2^{SD/PM}) = \frac{1}{16}(3 - 6t + 19t^2), \tag{43}$$

$$CS^{SD/PM} = \frac{(q_1 + q_2)^2}{2} = \frac{9}{32}(1-t)^2, \tag{44}$$

$$TR^{SD/PM} = t[(q_1 - k_1) + (q_2 - k_2)] = \frac{t}{4}(3 - 11t), \tag{45}$$

$$ED^{SD/PM} = g(q_1 - k_1)^2 + g(q_2 - k_2)^2 = \frac{g}{32}(61t^2 - 34t + 5). \tag{46}$$

The social welfare is given by

$$SW^{SD/PM} = \frac{1}{32}[15 - 5g + (34g - 6)t - (61g + 41)t^2]. \tag{47}$$

Therefore, in the first stage of the game, the government chooses the emission tax such that the social welfare in (47) is maximized, that is:

$$\frac{\partial SW^{SD/PM}}{\partial t} = 0 \Rightarrow t^{*SD/PM} = \frac{17g - 3}{61g + 41}. \tag{48}$$

From Eq. (48), $t^{*SD/PM} > 0$ if and only if $g > \frac{3}{17}$. Making use of the optimal tax in (48) and taking into account the constraint $g > \frac{3}{17}$, it is easy to see verify that $q_i^{SD/PM} > 0$, $k_i^{SD/PM} > 0$, and that $q_i^{SD/PM} > k_i^{SD/PM}$ is always fulfilled for any $\frac{3}{17} < g < \frac{14}{6}$. Using the optimal tax in (48), the equilibrium profits are:

$$\pi_1^{*SD/PM} = \frac{773g^2 + 866g + 493}{2(41 + 61g)^2}; \; \pi_2^{*SD/PM} = \frac{531g^2 + 382g + 251}{2(41 + 61g)^2}. \tag{49}$$

3.2.3 The owners' endogenous choice: the "sales" delegation game with pollution abatement and emission tax

By using the expressions in (10), (41) and (49), it is possible to build on the payoff matrix in Table 2 about the sales delegation game with pollution abatement and emission tax. First, to satisfy all technical constraints and obtain well identified equilibria in pure strategies for all strategic profiles, the analysis is confined to the following range of the environmental damage, $\frac{1}{4} < g < \frac{14}{6}$.

Table 2: The "sales" delegation game with abatement (payoff matrix)

Firm 1; Firm 2→ ↓	SD	PM
SD	$\pi_1^{*SD} = \frac{4(49g^2 + 42g + 25)}{(49g + 33)^2}$; $\pi_2^{*SD} = \frac{4(49g^2 + 42g + 25)}{(49g + 33)^2}$	$\pi_1^{*SD/PM} = \frac{773g^2 + 866g + 493}{2(41 + 61g)^2}$; $\pi_2^{*SD/PM} = \frac{531g^2 + 382g + 251}{2(41 + 61g)^2}$
PM	$\pi_1^{*PM/SD} = \frac{531g^2 + 382g + 251}{2(41 + 61g)^2}$; $\pi_2^{*PM/SD} = \frac{773g^2 + 866g + 493}{2(41 + 61g)^2}$	$\pi_1^{*PM} = \frac{48g^2 + 56g + 33}{2(11 + 16g)^2}$; $\pi_2^{*PM} = \frac{48g^2 + 56g + 33}{2(11 + 16g)^2}$

In order to derive all the game equilibria, the sign of the following set of profit differentials must be studied:

$$\Delta\pi_1 = \pi_i^{SD/PM} - \pi_i^{PM} ; \quad \Delta\pi_2 = \pi_i^{PM/SD} - \pi_i^{SD} \quad \Delta\pi_3 = \pi_i^{PM} - \pi_i^{SD} \text{ for } i = 1,2 \qquad (50)$$

An analytical inspection of the expressions in (50) reveals that

$$\Delta\pi_1 > 0; \quad \Delta\pi_2 < 0; \quad \Delta\pi_3 > 0,$$

from which the following result holds.

Result 2. *When the government levies an emission tax with the aim of maximising social welfare, the "sales" delegation game with pollution abatement generates the standard result (Vickers, 1985; Sklivas, 1987; Fershtman and Judd, 1987) in which the "sales" delegation is the dominant strategy, irrespective of the government's evaluation of the environmental damage. Therefore, (SD,SD) is the Nash equilibrium, but it is Pareto-dominated by the no delegation regime (PM,PM): firms are cast into a Prisoner's Dilemma.*

3.3 The "sales" vs "green" delegation game with pollution abatement and emission tax

This section investigates a delegation game in which owners offer managers either a standard "sales" contract or a "green" contract in the presence of a government levying an emission tax when firms have invested in abatement technologies. The case in which both owners offer a "green" delegation contract is precisely as in subsection 3.1.2, while the case in which both owners offer a "sales" delegation contract is as in subsection 3.2.1. Therefore, it remains to analyse the mixed case in which the two firms offer different incentive contracts.

3.3.1 Mixed case: only the owner of one firm delegate via a sales delegation contract

The owners' endogenous choice about the type of delegation needs the evaluation of the payoffs of the asymmetric game in which the owner of one firm, say Firm 1, designs a

"green" delegation contract while the rival, Firm 2, designs a sales delegation contract. The two managers maximisation problems give the first order conditions as in (12) for Firm 1 and as in (33) for Firm 2. Solving the system of the output reaction functions, one gets the output levels as a function of the incentives as in (13). By substituting these outcomes along with (i) condition B) in (12) into the profit function of Firm 1, and (ii) condition B) in (33) into the profit function of Firm 2, one gets the expressions of the firms' profits as a function of the managerial incentives. It follows that Firm 1's owners maximise profits with respect to b_1, and Firm 2's owners maximise profits with respect to b_2. This generates the system of reaction functions in the bonus space $b_1 = \frac{1}{13}(1-t-b_2)$ and $b_2 = \frac{1}{4}(1-t-b_1)$, whose solutions lead to the optimal bonuses $b_1^{GD/SD} = \frac{1}{17}(1-t)$ and $b_2^{GD/SD} = \frac{1}{17}(4-t)$. Thus, in equilibrium, it is follows that

$$q_1^{GD/SD} = \frac{1}{17}(5-t), \; q_2^{GD/SD} = \frac{1}{17}(8-t), \text{ and } k_1^{GD/SD} = \frac{1}{17}(18t-1), \; k_2^{GD/SD} = t$$

(51)

Making use of (51) lead to the producer surplus, consumer surplus, tax revenues and environmental damage in this asymmetric case:

$$PS^{GD/SD} = (\pi_1^{GD/SD} + \pi_2^{GD/SD}) = \frac{1}{578}(103 - 206t + 681t^2), \tag{52}$$

$$CS^{GD/SD} = \frac{(q_1+q_2)^2}{2} = \frac{169}{578}(1-t)^2, \tag{53}$$

$$TR^{GD/SD} = t[(q_1-k_1)+(q_2-k_2)] = \frac{2}{17}t(7-24t) \tag{54}$$

$$ED^{GD/SD} = g(q_1-k_1)^2 + g(q_2-k_2)^2 = \frac{g}{289}(577t^2 - 338t + 50) \tag{55}$$

The social welfare is given by

$$SW^{GD/SD} = \frac{1}{289}[136 - 50g + (338g - 34)t - (577g + 391)t^2] \tag{56}$$

In the first stage of the game, the government chooses the emission tax such to maximise the social welfare in (56), that is:

$$\frac{\partial SW^{GD/SD}}{\partial t} = 0 \Rightarrow t^{*GD/SD} = \frac{169g - 17}{577g + 391}. \tag{57}$$

From Eq. (57), $t^{*GD/SD} > 0$ if and only if $g > \dfrac{17}{169}$. Making use of the optimal tax in (57) and taking into account the constraint $g > \dfrac{17}{169}$, it can be verified that $q_i^{GD/SD} > 0$, $k_1^{GD/SD} > 0$ if $g > \dfrac{41}{145}$, $k_2^{GD/SD} > 0$ and $q_1^{GD/SD} > k_1^{GD/SD}$ is fulfilled for any $\dfrac{41}{145} < g < \dfrac{161}{25}$. By using the optimal tax in (57), the equilibrium profits are the following:

$$\pi_1^{*GD/SD} = \frac{51025g^2 + 39182g + 22753}{2(391 + 577g)^2}; \pi_2^{*GD/SD} = \frac{65425g^2 + 67982g + 37153}{2(391 + 577g)^2}. \tag{58}$$

3.3.2 The owners' endogenous choice: the "sales" vs "green" delegation game with pollution abatement and emission tax

By using the expressions in (21), (41) and (58), one can build on the payoff matrix summarised in Table 3 regarding the "green" vs "sales" delegation game. To satisfy all technical boundaries and obtain well identified equilibria in pure strategies for all strategic profiles, the analysis is restricted to the following range of the environmental damage, $\dfrac{41}{145} < g < \dfrac{161}{25}$.

Then, the study of the sign of the following set of profit differentials is required to derive the Nash equilibria of the game:

$$\Delta\pi_1 = \pi_i^{SD/GD} - \pi_i^{GD}; \quad \Delta\pi_2 = \pi_i^{GD/SD} - \pi_i^{SD} \quad \Delta\pi_3 = \pi_i^{GD} - \pi_i^{SD} \text{ for } i = 1, 2 \tag{59}$$

Table 3: The "sales" versus "green" delegation game with abatement (payoff matrix)

Firm 1; Firm 2→ ↓	GD	SD
GD	$\pi_1^{*GD} = \dfrac{48g^2 + 48g + 25}{2(11+16g)^2}$; $\pi_2^{*GD} = \dfrac{48g^2 + 48g + 25}{2(11+16g)^2}$	$\pi_1^{*GD/SD} = \dfrac{51025g^2 + 39182g + 22753}{2(391+577g)^2}$; $\pi_2^{*GD/SD} = \dfrac{65425g^2 + 67982g + 37153}{2(391+577g)^2}$
SD	$\pi_1^{*SD/GD} = \dfrac{65425g^2 + 67982g + 37153}{2(391+577g)^2}$; $\pi_2^{*SD/GD} = \dfrac{51025g^2 + 39182g + 22753}{2(391+577g)^2}$	$\pi_1^{*SD} = \dfrac{4(49g^2 + 42g + 25)}{(49g+33)^2}$; $\pi_2^{*SD} = \dfrac{4(49g^2 + 42g + 25)}{(49g+33)^2}$

An in-depth analytical inspection of (59) shows that:

$$\Delta\pi_1 > 0; \quad \Delta\pi_2 < 0; \quad \Delta\pi_3 > 0,$$

from which the following result holds.

Result 3. *When the government levies an emission tax with the aim of maximising social welfare, "sales" delegation (SD) is the dominant strategy irrespective of the government's evaluation of the environmental damage. Therefore, (SD,SD) is the Nash equilibrium, but it is Pareto-inefficient as the "green" delegation (GD) is payoff-dominant: firms are cast into a Prisoner's Dilemma. This gives each owner the incentive to design a "green" delegation contract rather than a "sales" delegation contract.*

Because of the strategic interactions, the design of a standard sales delegation contract to managers arises in equilibrium irrespective of the weight the government attaches to the environmental damage. This is because, without a direct inclusion of an incentive to abate emission in the compensation scheme, managers tend to behave more aggressively, expanding output and gaining market shares more with "sales" delegation than with "green" delegation. Moreover, with increasing output, the emission tax levied by the government is relatively

high. Owners would improve the profitability of their firms via "green" delegation: in fact, by reducing output (and thus emissions), firms would save on the cost of taxation due to a lower tax base as well as tax rate. Therefore, by choosing the standard sales delegation contract, owners are cast into a Prisoner's Dilemma.

4. Welfare analysis

Let us now briefly discuss the consequences of the government's tax rate decision and firms' strategic interactions on the overall social welfare (only equilibrium outcomes are analysed).

First, consider the "green" delegation game with emission tax as in subsection 3.1. Substituting out the expression of the optimal tax rate in Eq. (9) into the social welfare function Eq. (8) under PM, and the tax rate (20) into (19) under GD, one gets:

$$SW^{PM} = SW^{GD} = \frac{5(1+g)}{16g+11},$$

that is, the social welfare remains unaltered regardless of whether abatement choices are taken by owners or managers. Making use of (9) and (20), further analytical inspection reveals that also the consumer surplus and the environmental damage are equal under the two regimes. However, the pre-tax output in the two regimes are different. As owners can delegate to managers abatement decisions through an appropriate incentive, the government manipulates the tax rates such that the post-tax output is identical under the two regimes. This means that there exists a simple transfer of resources between the government, in terms of tax revenues, because of the different tax rates in the two regimes, and the firms, in terms of profits, because of the symmetrical more/less tax savings effect.

Second, consider now the standard "sales" delegation game with emission tax as in subsection 3.2. Substituting the optimal tax (9) into the social welfare expression (8) under PM, and the optimal tax (40) into (39) under SD, one gets:

$$\frac{16(1+g)}{49g+33} = SW^{SD} > SW^{PM} = \frac{5(1+g)}{16g+11},$$

that is, the social welfare under "sales" delegation is higher than when are the who take the relevant strategic decisions. A direct comparison of the tax rates (9) and (40) reveals that the emission tax rate under SD are higher than under PM. In addition, it can also be easily checked that the overall output level and, thus, the consumer surplus are higher under sales delegation than under profit maximisation. The higher tax rate in the SD regime implies also a higher incentive for the managers to abate emissions. On one hand, firms save more on taxation because of a higher abatement choice of the managers. On the other hand, however, the output expansion reduces the price and total revenues. However, due to a higher abatement, the environmental damage in the SD regime is larger than under PM. All these elements more than counterbalance the lower profits that firms obtain without delegation. To sum up, by setting the appropriate tax rates, the strategic interactions between firms lead the government to achieve the highest social welfare, in contrast to the firms' interests.

Finally, consider the SD versus GD game with emission tax as in subsection 3.3. Substituting the optimal tax (20) into the social welfare expression (19) for the "green" delegation, and the optimal tax (40) into (39) for the "sales" delegation, one finds the following result:

$$\frac{16(1+g)}{49g+33} = SW^{SD} > SW^{GD} = \frac{5(1+g)}{16g+11}.$$

Comparing the tax rates (20) and (40), it is easy to see that the emission tax rate under "sales" delegation is higher than under "green" delegation. The overall output level and thus the consumer surplus are also higher under "sales" delegation. As before, the higher tax rate in the SD regime implies 1) a higher government's total revenues and 2) a higher incentive for managers to abate emissions. On one hand, firms save more on taxes under "sales" delegation because of a higher abatement choice of the managers. On the other hand, the output

expansion reduces the price. Indeed, "green" delegation: 1) lowers production levels and allows price and revenues to fall not too much; and 2) induces the government to set a tax rate lower than with "sales" delegation, but higher than in the case of no-delegation, making the firms' tax savings larger. These combined effects have a positive impact on firms' profitability, leading to higher profits under "green" delegation than under "sales" delegation. Nonetheless, all these elements more than counterbalance the lower profits that firms obtain without delegation. To sum up, by setting the appropriate tax rates, the firms' strategic interactions allow the government to achieve the most desirable welfare, though this contrasts with the firms' interest.

5. Extension: horizontal product differentiation. A discussion

The robustness of the main results of the basic model developed in the previous section has been checked by assuming heterogeneous products (horizontal product differentiation) as in Singh and Vives (1984). The aim of this section is to briefly analyse this case. Under product differentiation, quantity-setting firms face the following linear inverse market demand:

$$p_i = 1 - q_i - dq_j, \ i, j = 1, 2; \ i \neq j \ ,$$

where p_i denotes the price of product of variety i, q_i and q_j are the output levels produced by firm i and firm j, respectively, and $0 < d < 1$ measures the degree of product differentiation (we consider only product substitutability). When $d = 0$ goods are totally differentiated, and each firm is a monopolist for its own product. Therefore, the firms' profit functions now are

$$\pi_i = (1 - q_i - dq_j)q_i - t(q_i - k_i) - \frac{k_i^2}{2}, \ i = 1, 2; \ i \neq j \ .$$

Applying the standard optimisation techniques and solving the game backwards (as in Section 3), one can first derive the firms' payoffs for every game. All the analytical

derivations are not here reported for economy of space, but they are available upon request from the authors. Then, making use of these payoffs, one can compute the profit differentials as in (31), (50) and (59) and the relevant parametric constraints as shown in Figures 1, 2 and 3.

Figure 2 depicts the game Nash equilibria and parametric constraints in the game GS versus PM under Cournot competition with differentiated products and emissions' abatement. The profit differentials in (31) generate 3 regions. The relevant parametric space is bounded by the lines

$$g_T^1(d) = -\frac{d^7 - 22d^5 + 7d^4 - 60d^3 - 24d^2 + 288d - 288}{3d^7 - 5d^6 - 59d^5 + 99d^4 + 324d^3 - 504d^2 - 576d + 864},$$

and

$$g_T^2(d) = -\frac{3d^7 - 5d^6 - 64d^5 + 94d^4 + 438d^3 - 588d^2 - 864d + 1152}{d^2(d-3)(d^4 - 12d^2 - 6d + 36)}.$$

Note that the red and green areas bound the technical non-feasibility of the abatement in Figures 2-4). In region A, the game equilibrium is (PM,PM) and this equilibrium is also Pareto-efficient. In region B, both (PM,PM) and (GD,GD) arise as Nash equilibria of the non-cooperative game; however, the PM Pareto-dominates GD. Finally, in region C, (GD,GD) is the unique Nash equilibrium because delegation is the dominant strategy, but it is Pareto inefficient: firms are cast into a Prisoner's Dilemma. Therefore, the main tenets of Result 1 also hold under product differentiation, with the additional result that (PM,PM) emerges as the unique Pareto-efficient equilibrium and, notably, when products are sufficiently differentiated, this holds irrespective of the government's evaluation of the environmental damage.

Figure 3 shows the Nash equilibria and parametric constraints in the case of the classical owners' "sales" delegation game under Cournot competition with differentiated products and

emissions' abatement. The profit differentials in (50) generate 3 regions. The relevant parametric space is bounded by the lines

$$g_a(d) = \frac{1}{3+d},$$

and

$$g_b(d) = -\frac{4d^4 + 17d^3 - 30d^2 - 48d + 64}{d^2(d+2)(2d-3)}.$$

In region A, (PM,PM) arises as the unique game equilibrium, and it is also Pareto-efficient. This result is of relevance because, with differentiated products and pollution abatement, the standard result of the emergence of strategic sales delegation and the Prisoner's Dilemma Structure of the game obtained in Fershtman and Judd (1987) is completely reversed. In region B, both (PM, PM) and (SD,SD) arise in equilibrium; however, (PM,PM) Pareto-dominates (SD,SD). Finally, in region C, sales delegation is the dominant strategy and, as a consequence, (SD,SD) is the unique Nash equilibrium, but it is Pareto-inefficient: firms face a Prisoner's Dilemma precisely as in the standard delegation game of Fershtman and Judd (1987). Thus, Result 2 is still valid in a wide area of the relevant parametric space, namely region C; however, the presence of heterogeneous products causes the significant result that, when products are sufficiently differentiated, (PM,PM) arises as the unique, Pareto-efficient equilibrium of the game and, notably, when goods are very differentiated, this applies regardless of the government's evaluation of the environmental damage.

Finally, Figure 4 shows the Nash equilibria and parametric constraints in the case SD versus GD under Cournot competition with differentiated goods and emissions' abatement. The profit differentials in (59) now generate 2 regions. The relevant parametric space is bounded by the lines

$$g_T^1(d) = -\frac{3d^8 - 2d^7 - 26d^6 + 52d^5 + 28d^4 - 336d^3 + 240d^2 + 576d - 576}{5d^8 + 16d^7 - 88d^6 - 208d^5 + 564d^4 + 864d^3 - 1584d^2 - 1152d + 1728}$$

and

$$g_T^2(d) = \frac{2d^8 + 13d^7 - 64d^6 - 218d^5 + 548d^4 + 1128d^3 - 1824d^2 - 1728d + 2304}{d^3(d^2 - 6)(5d^2 + 2d - 12)}$$

In region A, the "sales" delegation is the owners' dominant strategy, leading to (SD,SD) in equilibrium which is also Pareto-efficient. In region B, the "sales" delegation is again the owners' dominant strategy; therefore, the game equilibrium is (SD,SD). However, this equilibrium is Pareto-inefficient because (GD,GD) is payoff-dominant: the game has a Prisoner's Dilemma structure. As a consequence, in the presence of differentiated products, Result 3 still holds in an extremely wide area of the relevant parametric space, region B, with the additional result that (SD,SD) emerges as Pareto-efficient equilibrium when products are adequately differentiated, and when almost independent goods, irrespective of the government's evaluation of the environmental damage.
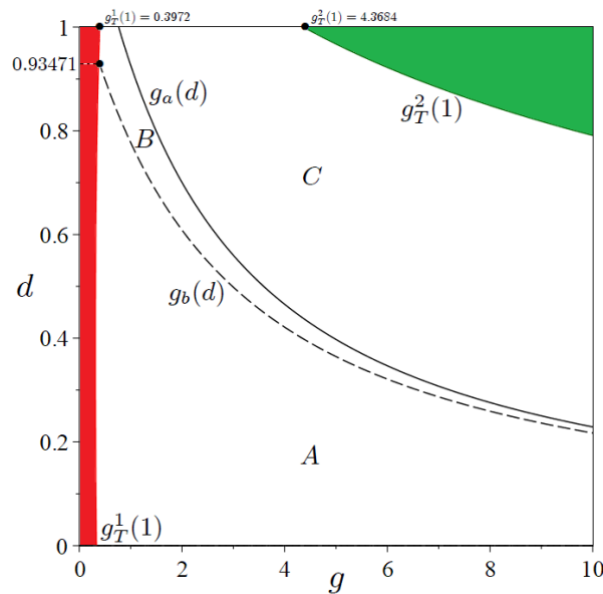

Figure 2: The "green" delegation game with differentiated products (Nash equilibria).
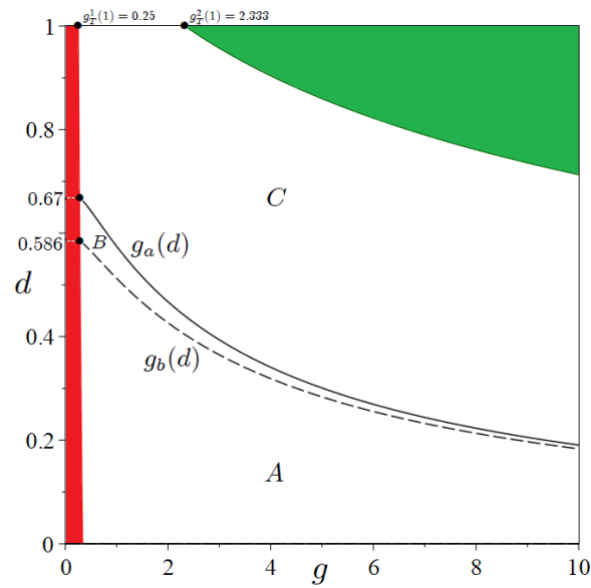
Figure 3: The "sales" delegation game with differentiated products (Nash equilibria).
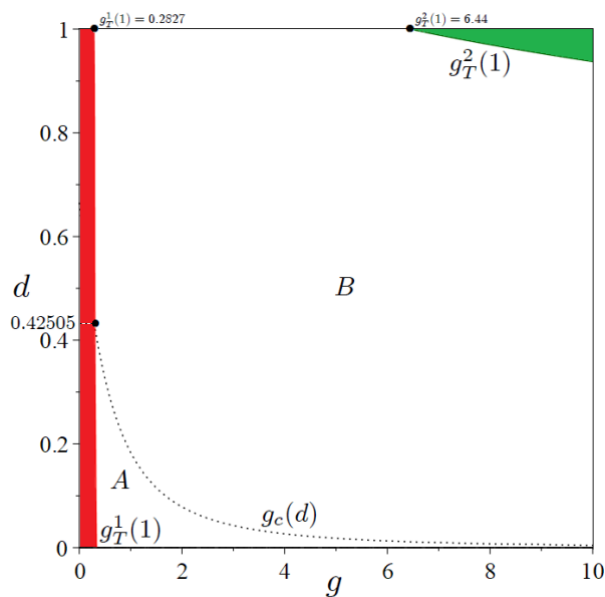

Figure 4: The "green" versus "sales" delegation game with differentiated products (Nash equilibria)

6. Conclusions

This article investigated the owners' decision whether to delegate to managers the choice of the abatement level in a Cournot duopoly homogeneous goods and pollution externalities, by

also assuming the existence of a government whose aim is to maximise social welfare using an emission tax. For doing this, the work developed a four-stage non-cooperative game (solved by backward induction) in which, first, the government fixes the emission tax, and then owners strategically choose whether to retain the choices of the abatement and output levels or delegate those decisions to a manager via a "green" or standard "sales" contract, by selecting the relative optimal incentive. Provided that the government attaches a sufficiently high weight to the environmental damage, a rich set of Nash equilibria emerges. In detail, in a game in which owners have to choose whether to delegate the abatement decision via a "green" contract or to retain this decision, two symmetric equilibria arise when the government attaches a low weight to the environmental damage: owners can either retain the strategic choices or delegate them through "green" incentive schemes. However, profits under the standard maximization rule payoff-dominate those under the "green" delegation contract. When the government evaluates the environmental sufficiently high, "green" delegation is the owners' dominant strategy; however, firms' owners face a Prisoner's Dilemma. Subsequently, the paper compares those results with a standard "sales" delegation game with emission abatement: the classical result in which managerial delegation emerges in equilibrium as a Prisoner's Dilemma is confirmed. Finally, in a four-stage game in which, first, the government sets the emission tax, and then owners decide whether to offer managers a "sales" delegation or a "green" delegation contract, it is shown that owners, in equilibrium, offer the former schema. However, owners are cast into a Prisoner's Dilemma because the "green" incentive scheme generates higher profits than the standard "sales" incentive, thus giving firms' owners an unilateral incentive to offer a "green" delegation contract. Those results are essentially robust to a model's extension which consider Cournot competition with differentiated products, with an extremely relevant novelty in the case of the standard "sales" delegation game with abatement. In fact, it is obtained that, when goods are sufficiently

differentiated, a unique, Pareto-efficient no-delegation equilibrium of the game emerges and, remarkably, when goods are extremely differentiated, this result holds regardless of the government's evaluation of the environmental damage, totally reversing the result of the Prisoner's Dilemma structure obtained in the standard strategic sales delegation game of Fershtman and Judd (1987).

This model is extremely simple and based on a set of precise assumptions that call for further extensions. A first line of research could be devoted to the study of different functional forms about demand and cost functions. A second line of development could be the introduction of different government's emission tax schedules diverse from the linear one here considered. A third line of research could be the study of different "green" incentive contracts based, for example, on the partial of total damage produced by the firms, to analyse how those different contracts would affect the decision about who would take abatement choices in managerial companies, and their impact of the firms' profitability. Those subjects are left to future research.

Conflict of Interest   The authors declare that they have no conflict of interest.

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