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Environmental corporate social responsibility, R&D and disclosure of "green" innovation knowledge☆

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ABSTRACT

The literature on the environment has analyzed how firms carry out R&D to reduce their pollutant emissions, assuming that they maximize profits. However, empirical evidence shows that firms are increasingly concerned about Environmental Corporate Social Responsibility (ECSR). Following that evidence, we consider that the objective function of firms incorporates the environmental damage they generate as part of their social concern. We find that how firms perform environmental R&D depends crucially on the degree to which they care about ECSR. If that degree is low enough, firms agree to set up an Environmental Research Joint Venture (ERJV) under which they coordinate their R&D investments and fully share their technological knowledge. This is the result obtained when firms maximize profits. If the degree is high enough, firms enter into an ERJV in which each fully shares its technological expertise but they do not coordinate their R&D investments. Finally, if the degree is intermediate, firms neither set up an ERJV nor disclose information. Social welfare is the highest and environmental damage the lowest if firms form an ERJV and coordinate their R&D investments. Therefore, the way in which firms organize their R&D activities is not always the most socially preferable.

1. Introduction

In the past few decades, concern by governments about the quality of the environment has led them to implement environmental laws and regulations to control pollution. Governments thus make firms internalize the environmental damage that they cause, because in the absence of such regulations firms have no incentive to do so.[1]

In recent years, governments have implemented voluntary environmental programs that complement the environmental measures that they have traditionally been using (such as environmental taxes and standards).[2] These programs encourage firms to take voluntary actions to reduce the impact of their activities on the environment beyond what is required by law. These voluntary environmental measures are framed within the concept of Environmental Corporate Social Responsibility (ECSR).[3] Empirical evidence shows that a large number of firms are concerned about ECSR due to pressure from governments, consumers, and environmentalists, among others (see Delmas and Montes-Sancho, 2010; Servaes and Tamayo, 2013). In this regard, PricewaterhouseCoopers (PwC) (2010) reports that 81% of firms provide CSR information on their websites. KPMG (Klynveld Peat Marwick Goerdeler) (2017) states that close to 75% of the firms analyzed in its survey issue CSR reports. One aspect to note is that the environment is a dominant issue in CSR reporting.

Environmental actions include investments that enable advanced

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[1] See, for example Barrett (1994), Ulph (1996), Helfand (1999), Requate (2006), Bárcena-Ruiz and Garzón (2014) and Ino and Matsumura (2021).

[2] These voluntary programs seek, among other objectives, to reduce hazardous waste and toxic emissions, improve energy efficiency and cut greenhouse gases (see Potoski and Prakash, 2005; Borck and Coglianese, 2009; Stenqvist and Nilsson, 2012). In addition, Lu et al. (2019) point out that European governments are encouraging firms to engage in ECSR because it helps to implement their environmental policy objectives on a voluntary basis.

[3] A broader concept is that of Corporate Social Responsibility (CSR), which means that firms decide voluntarily to contribute to a better society and a cleaner environment (European Commission, 2001). Albareda et al. (2007) point out that CSR is high on governments' agendas. In addition, Boulouta and Pitelis (2014) use a sample of developed countries and find that CSR activities can be important for national competitiveness so they should be promoted by governments.

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emission abatement technologies to be developed in order to improve the quality of the environment. Given that innovation is encouraged by both competition and cooperation among firms, their investment in "green" technologies depends on how they organize their R&D activities, for example through cooperative and non-cooperative agreements and research joint ventures. In addition, given their growing concern about the environment, many firms have increased their environmental R&D investment and are even making agreements to disclose their know-how in "green" technologies to rival firms free of charge (Ziegler et al., 2014).[4] In this regard, several firms have created the Eco-Patent Commons patent pool with the objective of fostering the sharing of technologies that help protect the environment (Hall and Helmers, 2013). For example, Ziegler et al. (2014) state that in 2010 Hewlett-Packard, a firm that cares about ECSR (see https://www.csrwire.com), granted free licenses on three patents on a battery recycling technology to the pool. Xerox has granted free patents that enable the time needed to remove toxic waste from soil and water to be cut from years to months. Finally, the multinational Dupont, a firm concerned about ECSR (see https://www.dupont.com), has contributed to the Eco-Patent Commons patent pool with a patent that uses enzymes to accelerate the conversion of certain non-recyclable plastics to fertilizers.[5] Additional examples can be found in the WIPO GREEN online platform for technology exchange. This is a program that connects providers and seekers of environmentally friendly technologies (see https://www3.wipo.int/wipogreen/en/). This means that some firms are voluntarily deciding to share their knowledge in "green" technologies with others. These issues are becoming increasingly important and are the focus of this paper.

The literature on R&D has mainly focused on strategic behavior by firms when deciding their R&D investment in the absence of environmental damage. Firms invest in R&D to reduce unit production costs, which permits them to gain market share at the expense of their rivals (see, e.g., d'Aspremont and Jacquemin, 1988; Kamien et al., 1992). This literature has also analyzed whether firms voluntarily disclose part or all of their technological knowledge for free in the absence of environmental damage. Poyago-Theotoky (1999) shows that whether firms disclose part or all of their technological knowledge depends on how they organize their R&D activities. She finds that firms do not reveal their information when they choose their R&D non-cooperatively but fully share it under cooperative R&D. Tesoriere (2008) analyzes how the disclosure of information between firms affects collusive agreements between them. Bárcena-Ruiz and Garzón (2020) consider a public firm that competes with a private one and find that only the public firm fully discloses its information when firms choose R&D investment levels non-cooperatively. Finally, Dong and Bárcena-Ruiz (2021) find that CSR is a factor that encourages firms to disclose their R&D knowledge, which speeds up the innovation process.[6]

The literature on R&D has been extended to consider environmental issues. Firms invest in environmental R&D in order to develop new technologies to reduce pollutant emissions (see, e.g., Lambertini et al., 2017; Wang, 2021; Xu et al., 2022). Taking as a reference the pioneering papers by d'Aspremont and Jacquemin (1988) and Kamien et al. (1992) the literature on the environment has considered several ways in which firms perform R&D to reduce pollutant emissions: (i) Environmental R&D competition, under which each firm decides its own environmental R&D investment level to maximize its own profit; (ii) Environmental R&D cartelization, which means that firms choose environmental R&D investment levels to maximize joint profits; (iii) Environmental Research Joint Venture (ERJV) competition, which means that each firm chooses its own R&D investment level to maximize its own profit but firms fully share their technological knowledge; and (iv) ERJV cartelization, under which firms coordinate their R&D investment levels to maximize joint profits and fully share their technological knowledge.[7]

The above issue has been analyzed when firms invest in R&D that reduces their pollutant emissions, under the assumption that the regulator is able to credibly commit to the setting of the environmental policy instrument. In this regard, Chiou and Hu (2001) consider R&D that reduces emissions when taxes are exogenously given. They compare R&D and production levels by firms under different ways of organizing R&D. Ouchida and Goto (2016a) extend that paper by considering that the government imposes an environmental tax on firms. They compare R&D, taxes, and production under different ways of organizing R&D, but do not analyze which of those ways firms prefer. They focus rather on the preference of the government. Other papers assume time-consistent emission taxes, under which taxes are chosen after R&D investment decisions are made. In this regard, Poyago-Theotoky (2007) considers cooperative and non-cooperative environmental R&D and finds that firms prefer to perform R&D cooperatively. Ouchida and Goto (2016b) extend that paper by also considering an ERJV. They assume that without an ERJV the spillover is exogenously given and that under an ERJV firms fully disclose their knowledge. They find that firms prefer ERJV cartelization.

In this paper, we assume that the regulator is able to credibly commit to the setting of the environmental policy instrument.[8] We extend previous work in three ways: Firstly, we consider that firms are engaged in ECSR, so they voluntarily reduce emissions since their objective function takes into account the environmental damage they generate.[9] Secondly, we assume that firms can decide what information to disclose to competitors when conducting environmental R&D non-cooperatively. Following Kamien et al. (1992), under an ERJV firms agree fully to disclose their R&D knowledge. Thirdly, we analyze which way of organizing R&D is preferred by firms.

The model considered in this paper is the following: We consider a market with two firms that produce a homogeneous good whose production process damages the environment. The government levies an environmental tax to make firms internalize their pollutant emissions, and is able to credibly commit to the setting of the tax. Firms are concerned about ECSR, so their objective function incorporates the environmental damage that they generate as part of their social concern. The total emission level of each firm can be reduced directly through its own R&D investment and indirectly through the technology that the rival firm discloses for free. Firms may organize R&D activities in three ways: R&D competition, ERJV competition, and ERJV cartelization. Under R&D competition firms decide whether to disclose their R&D

[4] Scott (2005) points out that environmental R&D investment is an example of socially responsible behavior by firms. His empirical study supports the hypothesis that socially responsible corporate investments in environmental R&D increase with corporate self-interest in reducing pollution caused by toxic emissions.

[5] See https://www.sony.com/en/SonyInfo/News/Press/200809/08-0909E/.

[6] Dong et al. (2021) study cooperative and non-cooperative R&D when firms are consumer-friendly.

[7] One of the objectives of a research joint venture for firms is to share the results of their research.

[8] This timing is widely used when analyzing environmental issues. See, for example, Chiou and Hu (2001), Gautier (2014), Tsai et al. (2015), Ouchida and Goto (2016a), Lambertini et al. (2017), Wang (2021) and Bárcena-Ruiz and Sagasta (2022).

[9] The literature that analyzes the environmental policies implemented by governments when firms care about social concerns usually measures those concerns through the consumer surplus. This means that their objective functions are a convex combination of the consumer surplus and profit, so no account is taken of their pollutant emissions (see Fanti and Buccella, 2017a, 2017b, 2018; García et al., 2018; Leal et al., 2018; Planer-Friedrich and Sahm, 2020; Bárcena-Ruiz and Sagasta, 2021). Other contributions consider that the objective function of firms that care about CSR incorporates environmental damage as part of their social concerns (see Lambertini and Tampieri, 2015; Lee and Park, 2019; Fukuda and Ouchida, 2020; Xu and Lee, 2022). We follow the latter approach in our paper.

knowledge, but under an ERJV firms agree to fully share their knowledge.

We show in the paper that the degree to which firms care about ECSR affects the decision by firms and governments differently under the different ways of organizing R&D. Under R&D competition, we unexpectedly find that firms that care about ECSR may generate more pollutant emissions than profit-maximizing firms. When the concern of firms about ECSR is low enough, they pay less tax and produce and abate more than a profit-maximizing firm, resulting in higher emissions as this concern increases. However, when the concern of firms about ECSR is high enough the tax is nil, so as concern increases firms produce less and abate more, generating lower emissions. Under both ERJV competition and ERJV cartelization, when concern increases firms produce and abate less, generating lower emissions.

We find that how firms organize their R&D activities depends crucially on their degree of concern regarding ECSR. When firms are profit maximizers, they agree to set up an Environmental Research Joint Venture under which they coordinate their R&D investments and fully share their technological knowledge (ERJV cartelization).[10] In the case of environmentally friendly firms, we find the same result when the degree of ECSR concern is low enough. However, if that degree is high enough, firms enter into an Environmental Research Joint Venture in which they fully share their technological expertise but do not coordinate their R&D investments (ERJV competition). Finally, if the degree is intermediate, firms neither set up an ERJV nor disclose information (Environmental R&D competition). Therefore, the degree of ECSR concern is a factor to be taken into account in explaining how firms organize R&D activities that reduce their pollutant emissions.

We also analyze consumer surplus, environmental damage, and social welfare under the three ways of organizing R&D investment. We find that social welfare is the highest and environmental damage the lowest under ERJV cartelization. Therefore, for low values of ECSR the way in which firms choose to organize their R&D activities leads to the socially preferred outcome. However, for higher values of ECSR, how firms organize their R&D activities may lead to lower consumer surpluses and social welfare and greater environmental damage. In such cases, the government could adopt economic policy measures aimed at reducing environmental damage and increasing social welfare.

We extend the analysis to consider that first the government commits to the environmental policy, then firms decide how to organize their environmental R&D. We find that the government sets the tax that makes firms choose ERJV cartelization, the form of organizing environmental R&D that generates the highest social welfare. Therefore, governments may use environmental policy to shape firms' organization of environmental R&D activities.

There is evidence that partially supports the results obtained in this paper. For example, the ERJV competition case can be seen as the situation of firms that belong to the Eco-Patent Commons pool which develop patents without collaboration and then make them public. For the ERJV cartelization case, De Marchi (2012) considers data from the Spanish Technological Innovation Panel and finds that 37.6% of the environmental innovators considered in the sample cooperated with external partners. There is also evidence of firms that do not cooperate in environmental R&D and keep their innovations private.

The rest of the paper is organized as follows: Section 2 describes the framework of analysis. Section 3 analyzes R&D competition, ERJV competition, and ERJV cartelization. Section 4 compares the results for the three cases. Section 5 considers an alternative timing of the game and Section 6 concludes.

[10] Ouchida and Goto (2016b) show that when the government has no precommitment ability for an emission tax rate and firms are profit-maximizers, ERJV cartelization is the most profitable scenario for the firms. We find that this result also holds when the government has commitment ability and firms care about ECSR for low values of environmental concern by firms.

2. The model

We consider a market in which there are two firms, denoted by 1 and 2, that produce a homogeneous good. The inverse demand function is given by $p = A - q_1 - q_2$, where p denotes the market price and q_i is the output of firm i, $i = 1, 2$.

Firms are engaged in Cournot competition, and their production process releases environmentally damaging emissions. Each unit of output produced by firms causes one unit of pollutant emission. The government implements an environmental tax, t, per unit of pollution to make firms internalize their pollutant emissions. Firms can prevent pollution and therefore reduce their tax burden by carrying out environmental R&D. Following Poyago-Theotoky (2007), Ouchida and Goto (2016b) and Lambertini et al. (2017), it is assumed that R&D investment seeks to reduce the environmental pollution from production. We denote by z_i the emission abatement level of firm i due to its R&D investment. Firm i's total emission level is given by:

$$e_i = q_i - z_i - \beta_j z_j, i \neq j; i, j = 1, 2 \tag{2.1}$$

where $\beta_j \in [0,1]$ is the R&D spillover parameter that measures the amount of information that firm j discloses for free to firm i. Therefore, the total emission level of firm i can be reduced directly through its own R&D investment and indirectly through the technology that firm j discloses.

Abating emissions entails a quadratic cost, which is given by $r(z_i) = d{z_i}^2$, reflecting diminishing returns on R&D expenditure. Parameter d measures the efficiency of R&D technology. In addition, firms have a constant marginal cost of production c. The environmental damage caused in the country by the pollutant emissions of the firms is given by $ED = ED_1 + ED_2$, where the environmental damage caused by firm i is given by $ED_i = e_i^2/2$, $i = 1, 2$. Our analysis is thus confined to the case in which firms are located in different zones of the country and each firm generates damage only in its own zone.[11]

The profit function of firm i is given by:

$$\pi_i = (p - c)q_i - t_i(q_i - z_i - \beta_j z_j) - d{z_i}^2, i \neq j; i, j = 1, 2. \tag{2.2}$$

To simplify the presentation of the results we assume without loss of generality that $d = 1/2$.[12]

We assume that both firms are environmentally responsible. Following Lambertini and Tampieri (2015), Lee and Park (2019), and Fukuda and Ouchida (2020), among others, we assume that the objective function of the firms incorporates environmental damage as part of their social concern. That is, firms care about their pollutant emissions and thus internalize their own shares of pollution. Given that a firm can directly influence its own production system, internalizing pollution leads it to invest in cleaner technologies to reduce the environmental impact of its own production. However, it can also influence the

[11] This assumption makes it easier to model the fact that the objective function of each firm takes into account the environmental damage that it generates (see Lambertini and Tampieri, 2015).

[12] Parameter d can be interpreted as the state of the technology, so larger values of parameter d imply technologies that are more inefficient. In the paper, we consider $d = 1/2$ since, in equilibrium, all three ways of organizing R&D are possible. When parameter d varies, some of the ways of organizing R&D no longer occur in equilibrium. Specifically, for sufficiently low values of parameter d (e.g., for $d = 0.2$), firms obtain higher profits under ERJV competition than in the other two cases. For intermediate values of parameter d, in equilibrium, all three ways of organizing R&D may arise in equilibrium (e.g., for $d = 1/2$): ERJV cartelization for a low enough θ, Environmental R&D competition for intermediate values of θ, and ERJV competition for a high enough θ. Finally, if parameter d is high enough, we find that for low values of parameter θ firms prefer Environmental R&D competition, while for high enough values of parameter θ firms prefer ERJV competition. A more detailed analysis of this case is available upon request.

pollution emitted by its rival if it decides to disclose its R&D knowledge. Therefore, the objective function of firm i is given by[13]:

$$V_i = \pi_i - \theta ED_i, i = 1, 2. \tag{2.3}$$

where parameter θ, $\theta \in [0, 1]$, is assumed to be exogenously given and equal for both firms, and to represent the degree of ECSR, i.e. the weight that firm i places on the environmental damage that it causes in addition to its profits. Hence, $\theta = 0$ means that firm i is only concerned about its profit, and the higher the parameter θ is, the more concerned firm i is about environmental damage.

There are factors that could lead in some situations, to the degree of social responsibility internalized by firms being exogenously determined. In today's economies, firms are under pressure from governments, supranational organizations, environmental organizations and consumer associations, among others, to make them internalize the environmental damage that they generate. In addition, in other industries and sectors there are firms concerned about ECSR which could lead other firms to imitate them. To some extent, some firms could adopt the proposals of the aforementioned organizations or imitate the behavior of other firms, so ECSR could be considered as exogenously given.[14]

As usual, the consumer surplus is given by $CS = (q_1 + q_2)^2/2$ and the total taxes collected by the government are $T = t(e_1 + e_2)$. Social welfare includes the profits of both firms, the consumer surplus, the total taxes collected by the government, and the environmental damage:

$$W = \pi_1 + \pi_2 + CS + T - ED. \tag{2.4}$$

As is well known, long-term variables that affect future decisions of the government and firms are set up before short-term ones made for a short time. The implementation of an environmental policy by the government is a long-term decision. In addition, the decision by firms on how to organize R&D is also a long-term decision since it may extend over time and affect how firms will act in the future. Short-term decisions taken by the government and firms, respectively, are the specific environmental policy and the level of R&D investment. Therefore, in our model, firms decide how they will organize R&D before the optimal tax is chosen by the government.

We analyze three possible ways of organizing R&D (see Kamien et al., 1992; Chiou and Hu, 2001; Ouchida and Goto, 2016b): (i) R&D competition, where firms determine their R&D investment non-cooperatively and decide how much of their R&D knowledge to disclose; (ii) Environmental Research Joint Venture (ERJV) competition, under which firms decide their R&D investment non-cooperatively and agree to fully share the results of their R&D investment; and (iii) ERJV cartelization, where firms cooperatively decide their R&D investment to maximize their joint profits and agree to fully share the information about R&D results.[15]

To analyze how firms endogenously choose the way in which they perform environmental R&D we consider a five-stage game with the following timing. In the first stage the firms decide how to organize environmental R&D. In the second stage the government decides on the environmental tax that maximizes social welfare given by (2.4).[16] In the third stage the firms choose their R&D levels to maximize their respective objective functions. In the fourth stage of the R&D competition case each firm decides how much of the knowledge created in the third stage to disclose. In the two ERJV models, it is assumed that firms fully share their R&D results ($\beta_1 = \beta_2 = 1$) so there is no fourth stage. Finally, in the fifth stage, firms choose their output levels. We solve the game backwards to get a subgame perfect equilibrium.

3. Analysis and results

Given that in the first stage each firm decides whether or not to set up an ERJV with its rival, there are three subgames to be analyzed: environmenal R&D competition, ERJV competition, and ERJV cartelization.

3.1. Environmental R&D competition

First, we analyze the case where firms determine their R&D investment non-cooperatively and decide how much of their R&D knowledge to disclose. We denote this case by superscript n. In the fifth stage, firm i chooses the production level, q_i, that maximizes V_i given by (2.3). Solving this problem, we obtain that the equilibrium outputs of each firm are as follows:

$$q_i = \frac{(A - c - t)(1 + \theta) + \theta(2 - \beta_i + \theta)z_i - \theta\left(1 - 2\beta_j - \theta\beta_j\right)z_j}{(1 + \theta)(3 + \theta)}, i \neq j; i, j = 1, 2. \tag{3.1}$$

The outputs of the firms depend on their environmental R&D, their disclosure of information, their environmental concern, and the environmental tax. It can be shown, from (3.1), that an increase in the emissions abatement level of firm i increases its output ($\frac{\partial q_i}{\partial z_i} = \frac{\theta(2-\beta_i+\theta)}{(1+\theta)(3+\theta)} > 0$) since a greater z_i means paying lower taxes. The effect of an increase in z_j on firm i's output depends on the information disclosed by firm j ($\frac{\partial q_i}{\partial z_j} = -\frac{\theta\left(1-(2+\theta)\beta_j\right)}{(1+\theta)(3+\theta)}$). If firm j fully discloses its information for free ($\beta_j = 1$), firm i produces more since it saves emission abatement costs and pays less taxes ($\frac{\partial q_i}{\partial z_j} > 0$). If firm j does not disclose its information ($\beta_j = 0$), firm j obtains a greater market share by investing more in R&D which decreases the output level of firm i ($\frac{\partial q_i}{\partial z_j} < 0$). Finally, an increase in the emission tax causes a greater cost for firm i so that firm reduces its output ($\frac{\partial q_i}{\partial t} < 0$).

In the fourth stage, each firm decides how much of the knowledge created in the third stage to disclose. Firm i chooses the disclosure level that maximizes V_i given by (2.3), where q_i is given by (3.1). The following first order conditions emerge:

$$\frac{\partial V_i}{\partial \beta_i} = -\frac{(2 + \theta)\theta z_i q_i}{(1 + \theta)(3 + \theta)}, i \neq j; i, j = 1, 2.$$

The output of firm i is positive, $q_i > 0$, which means that $\partial V_i / \partial \beta_i < 0$. Therefore, in equilibrium each firm decides not to disclose information,

[13] Following Lambertini and Tampieri (2015), Hirose et al. (2017), Lee and Park (2019), and Buccella et al. (2022), among others, each firm is concerned with its own environmental damage, rather than with the total environmental damage.

[14] We have tried to solve the model assuming that θ is endogenously determined. When solving the stage where firms choose the level of environmental R&D that maximizes their objective functions, we find that the equilibrium values for environmental R&D are cubic expressions with respect to θ_1 and θ_2. This makes it impossible to solve the game. This problem also arises in other papers analyzing similar issues (see, for example, Fukuda and Ouchida, 2020, footnote 20).

[15] There is a fourth case: R&D cartelization. In this case firms cooperatively decide their R&D investment levels and how much of their R&D knowledge to disclose. As firms cooperate in R&D and in equilibrium they choose to fully disclose their knowledge. This case is thus effectively the same as ERJV cartelization, so we omit it.

[16] We assume that the regulator is able to credibly commit to setting the environmental tax, so taxes are decided before R&D investments. This applies, for example, when the regulator wants to comply with the environmental policy that it announces or in the framework of binding international climate agreements when countries are expected to comply with those agreements. This timing means that the government decides its environmental policy with the aim of influencing the R&D decisions of firms, so taxes are decided before R&D decisions.

so $\beta^n = 0$. If firm i discloses information for free to firm j, the latter becomes more competitive in the product market since it can save R&D investments and pay less taxes. As a result, firm j gains market share and profits at the expense of firm i, which leads firm i not to disclose information.

In the third stage, firm i chooses the environmental R&D level, z_i, that maximizes V_i given by (2.3). Differentiating (2.3) with respect to z_i, the first order condition is derived as follows:

$$\frac{dV_i}{dz_i} = \underbrace{\frac{\partial V_i}{\partial q_i}\frac{\partial q_i}{\partial z_i}}_{=0} + \underbrace{\frac{\partial \pi_i}{\partial q_j}\frac{\partial q_j}{\partial z_i}}_{\substack{strategic\\effect}} + \underbrace{\theta(q_i - z_i)}_{\substack{ECSR\\effect}} + \underbrace{t}_{\substack{tax\\effect}} - \underbrace{r'(z_i)}_{\substack{cost\\effect}} = 0. \tag{3.2}$$

There are five terms in Eq. (3.2) that jointly determine firm i's environmental R&D decision. Firm i chooses q_i to maximize (2.3), so using the envelope theorem the first term is zero. The strategic effect indicates that firm i's pollution abatement indirectly affects its profit by affecting its rival's output. Given the R&D level of the rival firm, an increase in the R&D level of firm i reduces the output of its rival (since $\beta^n = 0$), increasing firm i's profit so the strategic effect is positive. This gives firm i an incentive to increase its environmental R&D investment in order to increase its own profit by decreasing its rival's output. The third term represents the effect of an increase in R&D investment by firm i on the environmental damage that it causes.[17] This term is positive because the firms are environmentally concerned, so firm i has an incentive to abate more in order to decrease its environmental damage, thus increasing V_i.[18] The fourth term represents the tax effect and measures the marginal effect of a change in firm i's abatement on the environmental taxes that it pays. This effect is positive because an increase in firm i's R&D investment reduces its emissions and its tax payment, thus increasing its profit. Finally, the last term is negative and represents the effect of R&D cost.

From (3.2), the following equilibrium abatement levels emerge:

$$z_i = \frac{(A-c)\theta(2+\theta)^2 + t\left(9 + 11\theta + 3\theta^2\right)}{(3+2\theta)\left(3 + 6\theta + 2\theta^2\right)}, i \neq j; i, j = 1, 2. \tag{3.3}$$

Eqs. (3.1) and (3.3) show that an increase in the tax chosen by the government makes firm i abate more and produce less, which reduces its emission level.

In the second stage, the government decides the environmental tax that maximizes social welfare, given by (2.4), taking as given the equilibrium behavior of the firms in the previous stages. Solving this problem, the following emerges:

$$t^n = \frac{(A-c)\left(27 + 3\theta - 78\theta^2 - 86\theta^3 - 35\theta^4 - 5\theta^5\right)}{243 + 606\theta + 540\theta^2 + 202\theta^3 + 27\theta^4} \tag{3.4}$$

The equilibrium values of outputs, abatement and emission levels, profits, consumer surplus, environmental damage, and social welfare obtained in this case are shown in Appendix A. From (3.4) and the results shown in Appendix A the following emerges.

Proposition 1. Under environmental R&D competition:

(i) if $\theta < 0.4729$, then $\partial t^n/\partial\theta < 0$, $\partial z^n/\partial\theta > 0$, $\partial q^n/\partial\theta > 0$, $\partial e^n/\partial\theta > 0$, $\partial(t^n e^n)/\partial\theta < 0$, $\partial CS^n/\partial\theta > 0$, $\partial\pi^n/\partial\theta > 0$, $\partial ED^n/\partial\theta > 0$, and $\partial W^n/\partial\theta > 0$;

(ii) if $\theta \geq 0.4729$, *then* $t^n = 0$, $\partial z^n/\partial\theta > 0$, $\partial q^n/\partial\theta < 0$, $\partial e^n/\partial\theta < 0$, $\partial CS^n/\partial\theta < 0$, $\partial\pi^n/\partial\theta < 0$, $\partial ED^n/\partial\theta < 0$, $\partial W^n/\partial\theta > 0$ *for* $\theta < 0.5191$ *and* $\partial W^n/\partial\theta < 0$ *for* $\theta > 0.5191$.

This proposition shows that under R&D competition, when θ is low enough ($\theta < 0.4729$), firms produce and abate more as they become more concerned about ECSR, generating more emissions, which reduces the total taxes paid by firms and increases the consumer surplus, the profit of the firms, environmental damage, and social welfare. However, when θ is high enough ($\theta \geq 0.4729$) the tax is nil, and as firms become more concerned about ECSR they produce less and abate more, generating less emissions. This reduces consumer surplus, the profit of the firms, and environmental damage. Social welfare may increase or decrease.

The optimal environmental tax set by the government is decreasing in θ if $\theta < 0.4729$ ($\partial t^n/\partial\theta < 0$). The intuition is as follows: When firms do not care about the environment ($\theta = 0$) the optimal tax induces the social optimum through two factors. First, the optimal tax under imperfect competition takes into account underproduction due to firms' market power, which tends to reduce the optimal tax (the underproduction effect). Secondly, the tax increases to make firms internalize the environmental damage that they generate and pollute less (the pollution-internalization effect). The second effect dominates the first, resulting in a positive environmental tax. When firms care about ECSR, the optimal tax is also influenced by parameter θ. As θ increases firms become more environmentally concerned, so they take into account a higher percentage of the damage that they generate which, for a given tax, encourages them to produce and emit less. This strengthens the underproduction effect and weakens the pollution-internalization effect. As a result, the environmental tax decreases with θ ($\partial t^n/\partial\theta < 0$), so the total taxes paid by each firm decrease with θ ($\partial(t^n e^n)/\partial\theta < 0$). As θ continues to increase, the underproduction effect becomes stronger and for $\theta \geq 0.4729$ the optimal environmental tax set by the government is nil ($t^n = 0$) since the establishment of a positive tax is unnecessary for socially concerned firms.

If $\theta < 0.4729$, firms become more concerned about their pollutant emissions as θ increases, which leads them to abate more ($\partial z^n/\partial\theta > 0$).[19] Firms' output depends on three factors: The tax set by the government, their abatement levels, and how much they care about ECSR. First, as θ increases the government sets a lower tax, which encourages firms to produce more. Second, as θ increases firms become more concerned about their pollutant emissions, which leads them to abate more, and from (3.1) it emerges that the output of each firm increases with its abatement level and decreases with the abatement level of its rival (since $\beta^n = 0$). Thirdly, as θ increases firms become more concerned about their pollutant emissions by internalizing their share of pollution, which leads them to reduce their output. As firms do not disclose information, the effects that lead to an increase in output dominate those that lead to a reduction, so an increase in θ encourages firms to produce more ($\partial q^n/\partial\theta > 0$).

As firms' output increases with θ, the consumer surplus also increases with this parameter ($\partial CS^n/\partial\theta > 0$). Firms' profits increases with θ ($\partial\pi^n/\partial\theta > 0$), which also increases the producer surplus. This is because although a greater θ leads firms to abate more, which increases the costs of reducing emissions, it also means that firms produce more and pay lower taxes. Although firms abate more as θ increases, the facts that they do not disclose information and that they produce more leads to higher pollutant emissions ($\partial e^n/\partial\theta > 0$), which increases environmental damage ($\partial ED^n/\partial\theta > 0$). Finally, social welfare increases with θ due to the higher producer and consumer surpluses ($\partial W^n/\partial\theta > 0$).

If $\theta \geq 0.4729$ it results that $t^n = 0$, so as firms become more environmentally concerned they produce less, abate more, and pollute less ($\partial q^n/\partial\theta < 0$, $\partial z^n/\partial\theta > 0$, $\partial e^n/\partial\theta < 0$). This reduction in the output of firms leads to a lower consumer surplus ($\partial CS^n/\partial\theta < 0$). In addition, as θ increases firms abate more, which increases the costs of reducing emissions, results in lower profits for firms ($\partial\pi^n/\partial\theta < 0$), and decreases the

[17] The effect of an increase in the R&D investment of firm i on the environmental damage that it causes has two terms: a direct effect caused by the change in z_i, captured in the ECSR effect, and an indirect effect through the change in the output when firms change z_i, which goes to the first term of Eq. (3.2).

[18] Chiou and Hu (2001) consider profit-maximizing firms, so there is no ECSR effect in their paper.

[19] This happens even though the tax decreases with θ, which provides an incentive to abate less.

producer surplus. Environmental damage decreases with θ because firms emit less ($\partial ED^n/\partial\theta < 0$). Finally, social welfare increases with θ if $\theta < 0.5191$ and decreases with θ if $\theta > 0.5191$. When $\theta < 0.5191$ the effect of the reduction in environmental damage dominates, so welfare increases with θ. However, as θ increases the reduction in the consumer and producer surpluses comes to have a stronger effect, which reduces social welfare.

Next, we consider that firms agree to set up an ERJV whereby each firm fully shares its technological expertise but they do not coordinate their R&D investments.

3.2. Environmental research joint venture competition

In this case firms decide their R&D investment non-cooperatively but fully share the results of that investment (i.e. $\beta_i = \beta_j = 1$). This case is denoted by superscript c. Given that firms agree to fully disclose their knowledge, the fourth stage of the game does not apply. In the last stage, each firm chooses the production level, q_i, that maximizes V_i given by (2.3). The equilibrium outputs of each firm are obtained by substituting $\beta_i = \beta_j = 1$ in (3.1).

In the third stage, firm i chooses the environmental R&D level, z_i, that maximizes V_i given by (2.3). As shown in Eq. (3.2), when firms decide their R&D investment non-cooperatively, there are five terms that jointly determine firm i's environmental R&D decision. The sign and intuition of the effects, explained above for the case of R&D competition, are maintained for the case of ERJV competition except for the sign of the strategic effect. Firms fully share their R&D results ($\beta^c = 1$), so from (3.1) it emerges that an increase in the R&D level of firm i increases the output of its rival, reducing the profits of firm i. Thus, the strategic effect is now negative and, contrary to what happens under R&D competition, when firms form an ERJV the strategic effect reduces the incentives of firm i to invest in environmental R&D.

Solving the problem, the equilibrium abatement levels prove to be as follows:

$$z_i = \frac{(A-c)\theta(2+\theta)+t(9+4\theta)}{3\left(3+8\theta+3\theta^2\right)}, i \neq j; i,j = 1,2. \tag{3.5}$$

In the second stage, the government decides the environmental tax that maximizes social welfare given by (2.4). Solving this problem, the following emerges:

$$t^c = \frac{(A-c)(2-\theta)\left(9+11\theta+3\theta^2\right)}{180+154\theta+33\theta^2} \tag{3.6}$$

The equilibrium values of outputs, abatement and emission levels, profits, consumer surplus, environmental damage, and social welfare obtained in this case are shown in Appendix B. From (3.6) and the results shown in Appendix B the following emerges.

Proposition 2. Under ERJV competition: $\partial t^c/\partial\theta < 0$, $\partial z^c/\partial\theta < 0$, $\partial q^c/\partial\theta < 0$, $\partial e^c/\partial\theta < 0$, $\partial(t^c e^c)/\partial\theta < 0$, $\partial CS^c/\partial\theta < 0$, $\partial\pi^c/\partial\theta > 0$, $\partial ED^c/\partial\theta < 0$, and $\partial W^c/\partial\theta < 0$.

Proposition 2 shows that under ERJV competition firms pay lower taxes and abate, produce, and emit less as θ increases. As a result, the total taxes paid by each firm, the environmental damage, the consumer surplus, and social welfare all decrease with θ, and the profit of the firms increases with θ.

The environmental tax is positive and decreases with θ ($\partial t^c/\partial\theta < 0$) for the same reason as under R&D competition, so we omit the explanation here. However, under ERJV competition firms fully disclose their technological knowledge ($\beta^c = 1$), so each firm has an incentive to produce more than under environmental R&D competition. This means that under ERJV competition, as θ increases the underproduction effect is strengthened less and the pollution-internalization effect is weakened less than under R&D competition. As a result, the environmental tax decreases with θ less under ERJV competition than under R&D competition.

In contrast to the case of environmental R&D competition, the abatement level is decreasing in θ ($\partial z^c/\partial\theta < 0$). As usual, the direct effect of θ is to encourage firms to abate more. However, the facts that the tax decreases with θ and that firms fully disclose their technological knowdledge lead them to abate less. As a result, the abatement level of the firms decreases with θ.

An increase in θ encourages firms to produce less ($\partial q^c/\partial\theta < 0$). As noted above, three factors explain this result: First, the tax is decreasing in θ, leading firms to increase their output. Second, the abatement level is decreasing in θ, which, from (3.1), implies that firms produce less. Thirdly, as θ increases firms are more concerned about their pollutant emissions, so they are encouraged to reduce their output. The second and third effects dominate the first, so an increase in θ encourages firms to produce less.

Firms' output decreases with θ, so the consumer surplus also decreases with θ ($\partial CS^c/\partial\theta < 0$). Although the output of the firms is decreasing in θ, the fact that the optimal tax and firms' abatement level are decreasing in θ means that firms' profits increase ($\partial\pi^c/\partial\theta > 0$), which also increases the producer surplus. In addition, although the abatement level is decreasing in θ the lower output leads the firms to produce lower emissions ($\partial e^c/\partial\theta < 0$) and pay lower total taxes ($\partial(t^c e^c)/\partial\theta < 0$), which reduces the environmental damage ($\partial ED^c/\partial\theta < 0$). Finally, although the environmental damage is decreasing in θ and the producer surplus is increasing in θ, social welfare decreases with θ due to the effect of the consumer surplus and total taxes collected by the government ($\partial W^c/\partial\theta < 0$).

Next we consider the case in which firms agree to set up an ERJV whereby each firm fully shares its technological expertise and they coordinate their R&D investments.

3.3. Environmental research joint venture cartelization

This case is denoted by superscript k. In this case firms cooperate in R&D investment and fully share R&D results (i.e. $\beta_i = \beta_j = \beta^k = 1$). As in the case of ERJV competition, firms agree to fully disclose their knowledge, so the fourth stage of the game does not apply. In the last stage, the equilibrium outputs of each firm are the same as under ERJV competition.

In the third stage, firm i chooses the environmental R&D level, z_i, that maximizes $V_i + V_j$ given by (2.3). Differentiating $V_i + V_j$ with respect to z_i, the first order condition is derived as follows:

$$\begin{aligned}\frac{d\left(V_i+V_j\right)}{dz_i} =& \underbrace{\frac{\partial V_i}{\partial q_i}\frac{\partial q_i}{\partial z_i}}_{=0} + \underbrace{\frac{\partial \pi_i}{\partial q_j}\frac{\partial q_j}{\partial z_i}}_{\text{strategic effect}} + \underbrace{\theta\left(q_i - z_i - z_j\right)}_{\text{ECSR effect}} + \underbrace{t}_{\text{tax effect}} - \underbrace{r'(z_i)}_{\text{cost effect}} \\ &+ \underbrace{\frac{\partial V_j}{\partial q_j}\frac{\partial q_j}{\partial z_i}}_{=0} + \underbrace{\frac{\partial \pi_j}{\partial q_i}\frac{\partial q_i}{\partial z_i} + \theta\left(q_j - z_j - z_i\right) + t}_{\text{coordination effect}} = 0\end{aligned} \tag{3.7}$$

A comparison of expressions (3.2) and (3.7) shows that when firm i assesses the effect of increasing its environmental R&D investment there is an additional term under ERJV cartelization that is not present in the other two cases. This effect is referred to here as the coordination effect: It measures the marginal effect of a change in firm i's abatement on the objective function of firm j. It does not appear in the other two cases because in those cases firms do not coordinate their R&D investments. The coordination effect is formed by three terms: The first indicates that the R&D level of firm i indirectly affects the profit of its rival by affecting its own output. Given the R&D level of the rival firm, an increase in the R&D level of firm i increases its output, reducing the profit of firm j, so this term is negative. The second term is positive and measures the marginal effect of a change in firm i's abatement on the environmental damage caused by firm j. Given the R&D level of the rival firm and the fact that $\beta_i = 1$, an increase in the R&D level of firm i reduces both the emissions and environmental damage of firm j, increasing V_j. The third term measures the marginal effect of a change in firm i's abatement on the environmental taxes paid by firm j. Given the R&D level of the rival firm and the fact that $\beta^k = 1$, an increase in the R&D level of firm i reduces the emissions of firm j, reducing the total taxes paid by firm j and increasing its profit. The second and third effects are positive and dominate the first, so the coordination effect is positive, which encourages firm i to abate more.[20]

From (3.7), it emerges that the equilibrium abatement levels are:

$$z_i = \frac{2((A-c)\theta(2+\theta) + t(9+4\theta))}{9+42\theta+17\theta^2}, i \neq j; i,j = 1,2. \tag{3.8}$$

In the second stage, the government decides the environmental tax that maximizes social welfare given by (2.4). Solving this problem, the following emerges:

$$t^k = \frac{(A-c)\left(108+123\theta-26\theta^2-25\theta^3\right)}{1863+1626\theta+355\theta^2} \tag{3.9}$$

The equilibrium values obtained in this case are shown in Appendix C. From (3.9) and the results shown in Appendix C the following emerges.

Proposition 3. Under ERJV cartelization: $\partial t^k/\partial\theta > 0$ if $\theta < 0.2323$ and $\partial t^k/\partial\theta < 0$ if $\theta > 0.2323$, $\partial z^k/\partial\theta < 0$, $\partial q^k/\partial\theta < 0$, $\partial e^k/\partial\theta < 0$, $\partial(t^ke^k)/\partial\theta > 0$ if $\theta < 0.1875$ and $\partial(t^ke^k)/\partial\theta < 0$ if $\theta > 0.1875$, $\partial CS^k/\partial\theta < 0$, $\partial\pi^k/\partial\theta > 0$, $\partial ED^k/\partial\theta < 0$, and $\partial W^k/\partial\theta < 0$.

A comparison of Propositions 2 and 3 shows that the signs of the effect of a change in θ on the equilibrium values are the same under ERJV competition and ERJV cartelization, except when the effect of a change in θ on the equilibrium tax and tax payment for low values of θ is considered. We thus focus only on explaining the intuition of these two cases, as in the other cases the intuition is straighforward.

The optimal tax is increasing (decreasing) in θ if $\theta < 0.2323$ ($\theta > 0.2323$). Unlike the ERJV competition case, firms now choose emission abatements taking into account their effect on the objective function of the two firms, which gives rise to the coordination effect, which encourages each firm to increase its R&D investment, reducing emissions further. Therefore, the incentive to produce less as θ increases is weaker than under ERJV competition. This also means that firms produce less environmental damage as θ increases, which in turn means that both the underproduction effect and the pollution-internalization effects are weakened. When θ is low enough ($\theta < 0.2323$), the tax increases with θ ($\partial t^c/\partial\theta > 0$) because the pollution-internalization effect dominates (it is weakened less) due to the coordination effect. However, when θ is high enough ($\theta > 0.2323$), the tax decreases with θ ($\partial t^c/\partial\theta < 0$) because the underproduction effect dominates (as it is weakened less).

Total taxes paid by each firm increase with θ if $\theta < 0.1875$ ($\partial(t^ke^k)/\partial\theta > 0$) and decrease with θ if $\theta > 0.1875$ ($\partial(t^ke^k)/\partial\theta < 0$). This is because when θ is small ($\theta < 0.1875$), the fact that θ increases means that the increase in the tax is stronger than the emissions reduction; when θ is intermediate the emissions reduction ends up dominating ($0.1875 < \theta < 0.2323$); and when θ is large ($\theta > 0.2323$) both emissions and tax are reduced by θ.

3.4. Comparison of the results obtained in the three cases

Next, we compare the taxes set by the government and the production, abatement levels, emissions, and total taxes paid by the firms in the three cases considered.

Proposition 4. *In equilibrium*:

(i) $t^n > t^c > t^k$ *if* $\theta < 0.0451$, $t^c > t^n > t^k$ *if* $0.0451 < \theta < 0.2067$, *and* $t^c > t^k > t^n$ *if* $\theta > 0.2067$;

(ii) $z^k > z^n > z^c$ *if* $\theta < 0.1659$, $z^n > z^k > z^c$ *if* $\theta > 0.1659$, *and* $2z^k > 2z^c > z^n$;

(iii) $q^k > q^c > q^n$ *if* $\theta < 0.0707$, $q^k > q^n > q^c$ *if* $0.0707 < \theta < 0.3945$, $q^n > q^k > q^c$ *if* $0.3945 < \theta < 0.8132$, *and* $q^k > q^n > q^c$ *if* $\theta > 0.8132$;

(iv) $e^n > e^c > e^k$;

(v) $t^ne^n > t^ce^c > t^ke^k$ *if* $\theta < 0.2456$, $t^ce^c > t^ne^n > t^ke^k$ *if* $0.2456 < \theta < 0.3556$; *and* $t^ce^c > t^ke^k > t^ne^n$ *if* $\theta > 0.3556$.

In Proposition 4, the rankings crucially depend on the degree of ECSR of firms. We first compare the taxes set by the government in the three cases. When firms maximize profits ($\theta = 0$) it is obtained that $t^n > t^c > t^k$. The explanation of this result is as follows: Under R&D competition firms do not disclose information, so they only reduce emissions due to their own R&D. Under an ERJV all information is transmitted, so firms also reduce emissions due to their rival's R&D. This leads the government to set higher taxes under R&D competition than if firms engage in an ERJV. In addition, the positive coordination effect leads to lower taxes under ERJV cartelization than under ERJV competition.

As shown in Propositions 1 to 3, $\partial t^n/\partial\theta < 0$ if $\theta < 0.4729$ and $t^n = 0$ if $\theta \geq 0.4729$, $\partial t^c/\partial\theta < 0$ and $\partial t^k/\partial\theta > 0$ if $\theta < 0.2323$ and $\partial t^k/\partial\theta < 0$ if $\theta > 0.2323$. Therefore, the result obtained when firms maximize profits holds when concern about ECSR is low enough ($\theta < 0.0451$). As θ increases, t^n and t^c decrease, inducing firms to produce more due to the underproduction effect. However, as explained in Proposition 2, t^n decreases strongly because under R&D competition firms do not disclose information. In addition, $t^c > t^k$ for all θ due to the coordination effect, which encourages firms to invest more in environmental R&D under ERJV cartelization than under ERJV competition. This implies that $t^c > t^n > t^k$ for $0.2067 > \theta > 0.0451$ and $t^c > t^k > t^n$ for $\theta > 0.2067$.

We now compare the levels of R&D investment undertaken by firms in the different cases. When firms maximize profits ($\theta = 0$) it is obtained that $z^k > z^n > z^c$. The explanation of this result is the following: First, it is obtained that $z^k > z^c$ and $z^k > z^n$ for all values of θ due to the positive coordination effect noted in Eq. (11), which increases firms' incentives to invest in R&D under ERJV cartelization. Second, it emerges that $z^n > z^c$ for all values of θ because the strategic effect is positive (negative) under R&D (ERJV) competition, increasing (decreasing) firms' incentive to invest in environmental R&D. In addition, as seen in Propositions 1 to 3, $\partial z^n/\partial\theta > 0$, $\partial z^c/\partial\theta < 0$ and $\partial z^k/\partial\theta < 0$. This means that for a sufficiently low θ ($\theta < 0.1659$) the same result emerges as for $\theta = 0$: $z^k > z^n > z^c$. As $z^k > z^c$ and both z^k and z^c decrease with θ, it is obtained that $z^n > z^k > z^c$ for $\theta > 0.1659$. Finally, given that firms that engage in an ERJV fully disclose their information, the emissions that they abate are due to the R&D performed by both firms, so $2z^k > 2z^c > z^n$.

We now compare the output of the firms in the different cases. When firms maximize profits ($\theta = 0$) it is obtained that $q^k > q^c > q^n$. This result is explained mainly by the total taxes paid by each firm.[21] When $\theta = 0$ it emerges that $t^n > t^c > t^k$ and $2z^k > 2z^c > z^n$. Under ERJV cartelization firms pay lower taxes and abate more than in the other two cases, resulting in higher output. Regarding R&D competition and ERJV competition, firms produce less because they abate less in the former case, given that they choose not to disclose information and pay higher taxes.

As shown in Propositions 1 to 3, $\partial q^n/\partial\theta > 0$ for $\theta < 0.4729$ and $\partial q^n/\partial\theta < 0$ for $\theta \geq 0.4729$, $\partial q^c/\partial\theta < 0$ and $\partial q^k/\partial\theta < 0$. Therefore, the result obtained when firms maximize profits holds for a low enough θ ($q^k > q^c > q^n$ for $\theta < 0.0707$). It emerges that $q^k > q^c$ for all θ due to the coordination effect. When θ is low enough ($\theta < 0.4729$), given that q^n increases with θ while q^k and q^c decreases with θ, it is obtained that $q^k > q^n$

[20] The coordination effect is negative in the paper by Chiou and Hu (2001) because they assume that the environmental tax is exogenously given. In our model, if $\theta = 0$ the coordination effect is positive because the tax is endogenously determined.

[21] The abatement cost has less weight in the explanation; it can reinforce the effect of total taxes or have a weaker effect.

$> q^c$ if $0.0707 < \theta < 0.3945$ and $q^n > q^k > q^c$ *if* $0.3945 < \theta < 0.4729$. When θ is high enough ($\theta > 0.4729$), output decreases with θ in all cases but, given that under ERJV cartelization firms pay higher taxes than under R&D competition, output is lower in the first case ($q^n > q^k > q^c$ if $0.4729 < \theta < 0.8132$). Finally, if $\theta > 0.8132$ the fact that q^n decreases strongly with θ since $t^n = 0$, means that $q^k > q^n > q^c$. In this last case it emerges that $q^n > q^c$ because although firms reduce emissions less under R&D competition than under ERJV competition ($2z^c > z^n$), they pay less in taxes ($t^c > t^n$).

We now compare the emissions of the firms in the three cases. The emissions of each firm are a function of its production, their abatement level, and the amount of information that the rival firm discloses for free. When firms maximize profits ($\theta = 0$) it is obtained that $e^n > e^c > e^k$. In this case, as already seen, $2z^k > 2z^c > z^n$ and $q^k > q^c > q^n$. Output is higher under ERJV cartelization than under ERJV competition, but the greater emission abatement due to the coordination effect leads firms under ERJV cartelization to emit less ($e^c > e^k$). On the other hand, although output is higher under ERJV competition than under R&D competition, the greater reduction of emissions in the former case leads to lower emissions ($e^n > e^c$). When $\theta > 0$ the comparison of outputs in the three cases may differ from the case in which $\theta = 0$. Despite this, the fact that $2z^k > 2z^c > z^n$ gives the same result as when $\theta = 0$.

Proposition 4(*v*) shows that $t^c e^c > t^k e^k$ for all θ. This is due to the coordination effect, which leads firms to emit less under ERJV cartelization. The difference in the tax paid in the two cases is small, so greater emissions under ERJV competition lead to higher tax payments. As seen in Proposition 1, under R&D competition tax decreases sharply, reaching zero for $\theta \geq 0.4729$. If $\theta < 0.2456$ taxes are high under R&D competition so the tax payment is higher in this case than in the other two cases ($t^n e^n > t^c e^c > t^k e^k$). If $0.3556 > \theta > 0.2456$ the tax decreases sufficiently under R&D competition, which means that $t^c e^c > t^n e^n > t^k e^k$. Finally, if $\theta > 0.3556$ the tax is so low under R&D competition that $t^c e^c > t^k e^k > t^n e^n$.

4. Organization of environmental R&D

This section analyzes how firms organize their environmental R&D. This decision is made in the first stage of the game. By comparing the profits obtained in each form of organizing R&D, as analyzed in the previous sections and shown in Appendices A, B and C, the following result emerges.

Proposition 5. In equilibrium, if $\theta < 0.3615$ firms adopt ERJV cartelization; if $0.3615 < \theta < 0.6913$ firms choose environmental R&D competition; finally, if $0.6913 < \theta$ firms select ERJV competition.

Proof. See Appendix D.

The result shown in Proposition 5 is illustrated in Fig. 1. To explain this result it must be taken into account that firms' profits depend on three factors: Revenues (which depend inversely on ouput), tax payments, and abatement costs. How firms choose to organize R&D depends on which factors have most effect on firms' profits.

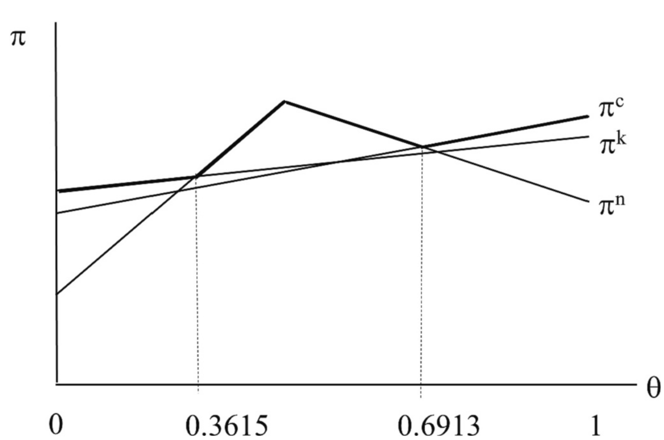

Fig. 1. Illustration of Proposition 5.

If firms maximize profits ($\theta = 0$) then ERJV cartelization is the preferred form of organization of R&D. This is because the coordination effect means that under ERJV cartelization firms invest more in R&D than in the other two cases ($z^k > z^n > z^c$) and a lower tax is set ($t^n > t^c > t^k$), which lead firms to produce more ($q^k > q^c > q^n$) and emit less ($e^n > e^c > e^k$). In that case, revenues are the lowest (since output is the highest), abatement costs are the highest, but firms pay less total taxes. Given that $\theta = 0$, tax payment has a significant effect on profits, which leads firms to choose ERJV cartelization. For $\theta < 0.3615$ this result holds. As seen in Propositions 1 to 3, for the values of θ mentioned, tax payments decrease with θ, and are highest for $\theta = 0$. As firms give little weight in their objective function to the damage that they generate, tax payment remains the factor that has most effect on profits, so firms choose ERJV cartelization. This result is consistent with the findings of Poyago-Theotoky (2007) and Ouchida and Goto (2016b), who consider that no firm is environmentally responsible. However, this result does not hold when firms' environmental concern is high enough ($\theta > 0.3615$). Therefore, ERJV cartelization is not always carried out by environmentally responsible firms, as it occurs when firms maximize their profits.

When $0.3615 < \theta < 0.6913$ firms choose R&D competition, so they do not cooperate in R&D and do not disclose information. This is because in this case tax payments are lower than in the other two cases. Emission abatement is the highest ($z^n > z^k > z^c$), so the abatement cost is also the highest. Finally, output is greater (so revenues are lower) than under ERJV competition and may be higher or lower than under ERJV cartelization. The effect of lower tax payments dominates, causing firms to prefer R&D competition.

When $\theta > 0.6913$ firms choose ERJV competition, so they disclose their information but do not cooperate in R&D. In this case, higher revenues are obtained than in the other two cases, since less is produced. In addition, this is the case where abatement is the lowest, so abatement costs are also the lowest. Finally, tax payments are the highest. Given that θ is high, tax payment is low in all three cases. Thus, revenues and abatement costs weigh more heavily on profits than tax payments, leading firms to choose ERJV competition.

Next we compare the consumer surplus, environmental damage, and social welfare under the three ways of organizing R&D analyzed. The following proposition emerges:

Proposition 6. In equilibrium, consumer surplus is the highest under ERJV cartelization if $\theta < 0.3945$ and if $\theta > 0.8132$; under environmental R&D competition it is the highest if $0.3945 < \theta < 0.8132$. Environmental damage is the highest under environmental R&D competition and the lowest under ERJV cartelization. Finally, social welfare is the highest under ERJV cartelization and the lowest under environmental R&D competition.

This Proposition shows that consumer surplus is the highest under ERJV cartelization if $\theta < 0.3945$ and if $\theta > 0.8132$, while it is the highest under R&D competition if $0.3945 < \theta < 0.8132$. As seen in Proposition 4, this is because the output of the firms is the highest in those cases. Proposition 6 also shows that environmental damage is the highest under R&D competition and lowest under ERJV cartelization. As seen in Proposition 4, this is due to the total pollutant emissions of the firms, since more pollution means greater environmental damage. Finally, social welfare is the highest under ERJV cartelization and lowest under R&D competition. The main reason why welfare is higher under ERJV cartelization than in the other two cases is that the environmental damage under ERJV cartelization is the lowest. For certain values of the parameter θ the lowest environmental damage under ERJV cartelization is supplemented by the highest producer surplus (for $\theta < 0.3615$) and the highest consumer surplus (for $\theta < 0.3945$ and $\theta > 0.8132$). The ranking of environmental damage and social welfare is consistent with

Ouchida and Goto (2016a), who also show that RJV cartelization generates the highest social welfare and the lowest environmental damage. Our results also show that consumer surplus depends on the degree of environmental concern of the firms.

According to Proposition 5, when firms choose how to organize R&D, they form an ERJV cartelization if $\theta < 0.3615$. This way of organizing R&D leads to the highest consumer surplus and social welfare and the lowest environmental damage. However, the way of organizing R&D chosen by the firms for other values of θ can be detrimental to consumer surplus, environmental damage, and social welfare. If $\theta > 0.3615$, an ERJV cartelization is socially desirable, but firms form an R&D competition (if $0.3615 < \theta < 0.6913$) or an ERJV competition (if $\theta > 0.6913$). These two ways of organizing R&D lead to higher environmental damage and lower social welfare than ERJV cartelization. Regarding consumer surplus, if $0.3945 < \theta < 0.6913$, firms form an R&D competition, which leads to the highest consumer surplus, but for other values of θ, the way of organizing R&D chosen by firms does not yield the highest consumer surplus. These results indicate that the government could take economic policy measures to increase social welfare and decrease environmental damage. For example, the policies adopted should be aimed at encouraging firms to cooperate in R&D and to disclose their information for $\theta > 0.3615$.

One policy could be to provide a lump sum subsidy to encourage firms to cooperate in environmental R&D. It can be shown that there is a lump-sum subsidy that can be given to firms to make them obtain greater profits, so that they prefer to choose ERJV cartelization over other ways of organizing environmental R&D. As it is a lump sum subsidy, it does not affect social welfare. Moreover, in all cases the amount of the lump-sum subsidy for firms to adopt ERJV cartelization is less than the reduction in environmental damage that is achieved. Economic policy could also take the form of a fixed-amount penalty for firms that generate excessive emissions. If a sufficiently large penalty is placed on those firms that exceed the emissions of firms that choose ERJV cartelization, e^k, firms would always choose this form of environmental R&D organization.

5. Alternative timing

In this section we assume a game in which the government first commits to the environmental policy and then firms decide how to organize their environmental R&D. As a result we consider a five-stage game with the following timing. In the first stage the government decides on the environmental tax that maximizes social welfare. In the second stage firms decide how to organize environmental R&D. The other stages of the game are as in Section 3. We solve the game backwards to get a subgame perfect equilibrium. As in Section 3, we assume that $d = 1/2$.

The third to fifth stages of the game are solved as in Section 3. In the second stage, for a given tax, firms choose the way of organizing their environmental R&D that generates the highest profits. We assume that if firms are indifferent between choosing environmental R&D competition, ERJV competition, and ERJV cartelization then they will choose the way of organizing their environmental R&D that generates the greatest social welfare.

We denote by $\pi^i(t)$ the profit of each firm if the government sets the tax t and firms organize environmental R&D in the form i ($i = n, c, k$); in that case the social welfare obtained is $W^i(t)$. In Appendix E we bring together the output, investment in environmental R&D, and profits of each firm and the social welfare obtained in the different cases as a function of t and θ.

A comparison of the profits obtained by firms under environmental R&D competition and ERJV competition reveals that $\pi^c(t) > \pi^n(t)$, so firms never choose environmental R&D competition for a given tax. This is because in that case firms do not disclose information, so they cannot take advantage of their rival's R&D, and a lower profit is obtained than in the other two cases, where firms do disclose information.

Comparing the profits obtained by firms under ERJV competition and ERJV cartelization we find that $\pi^k(t) > \pi^c(t)$ if $t > t^*$, $\pi^k(t) < \pi^c(t)$ if $t < t^*$ and $\pi^k(t) = \pi^c(t)$ if $t = t^*$. Under ERJV cartelization firms choose the level of R&D that maximizes $V_1 + V_2$, so they invest more in R&D than under ERJV competition for all t and θ. Moreover, in the former case emissions are lower than in the latter, so less tax is paid. Therefore, as shown Fig. 2, it is more profitable for firms to choose ERJV cartelization if the tax is sufficiently high (i.e. if $t > t^*$). In addition, the tax set by the government (see Appendix E) must meet the requirement that $t < t^{kh}$ to ensure that the emission level of the firms is positive in all cases.

In the first stage, the government chooses the tax that maximizes social welfare. If $t \geq t^*$ firms choose ERJV cartelization, so the government chooses the tax that maximizes $W^k(t)$ subject to $t \geq t^*$. If $t \leq t^*$ firms choose ERJV competition, so the government chooses the tax that maximizes $W^c(t)$ subject to $t \leq t^*$.

We first consider that $\theta < 0.1475$. If $t \geq t^*$, as can be seen in Fig. 2, firms choose ERJV cartelization and the government, as in Section 3, sets the tax $t = t^k$ and the social welfare obtained is $W^k(t^k)$. If $t \leq t^*$, firms choose ERJV competition. As $W^c(t)$ increases with t, the government sets the highest possible tax that makes firms choose ERJV competition, $t = t^*$, and the social welfare obtained is $W^c(t^*)$. Comparing the social welfare obtained under ERJV competition and ERJV cartelization we find that $W^k(t) > W^c(t)$ if and only if $t < t^W$, with $t^W > t^{kh} > t^*$. As a result, social welfare under ERJV cartelization is greater than under ERJV competition for the values that t and θ can adopt. It can be checked that $W^k(t^k) > W^c(t^*)$. As a result, if $\theta < 0.1475$ the government sets the tax $t = t^k$ and firms choose ERJV cartelization. As shown in Fig. 2, for firms to choose ERJV competition the government must greatly reduce the tax with respect to t^c, which reduces social welfare. This leads to higher social welfare if firms choose ERJV cartelization.

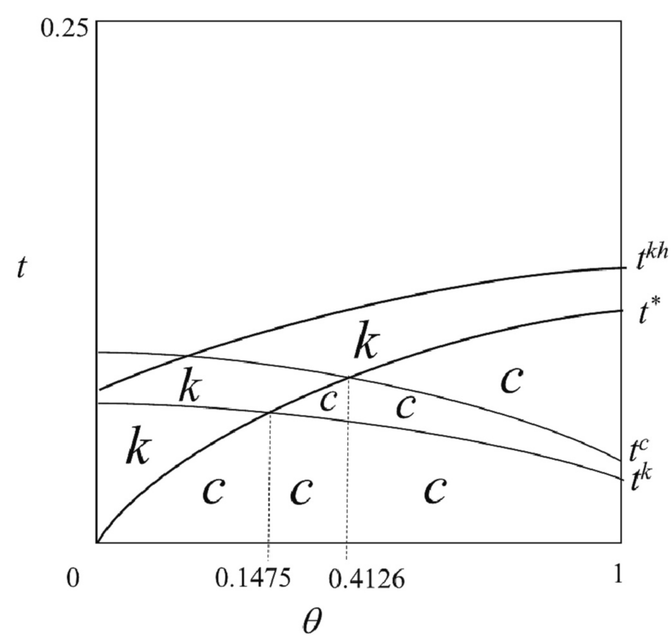

Fig. 2. Way of organizing environmental R&D chosen by firms as a function of t and θ.

We now consider that $0.1475 < \theta < 0.4126$. If $t \geq t^*$, $W^k(t)$ decreases with t so for firms to choose ERJV cartelization the government must set the lowest possible tax that achieves it, $t = t^*$; in that case the welfare obtained is $W^k(t^*)$. If $t \leq t^*$, $W^c(t)$ increases with t so the government sets the highest possible value of the tax, $t = t^*$; in that case the welfare obtained is $W^c(t^*)$. It can be seen that $W^k(t^*) > W^c(t^*)$ so the government sets the tax $t = t^*$ and firms choose ERJV cartelization. Note that for $t = t^*$ firms are indifferent between ERJV cartelization and ERJV competition, but ERJV cartelization generates higher social welfare.

Finally, we consider that $\theta > 0.4126$. If $t \geq t^*$, $W^k(t)$ decreases with t so the government sets $t = t^*$ and the social welfare obtained is $W^k(t^*)$. If $t \leq t^*$, the government sets the tax $t = t^c$ and the social welfare obtained is $W^c(t^c)$. It can be checked that $W^k(t^*) > W^c(t^c)$ for $\theta > 0.4126$. Therefore, in this area the government sets the tax $t = t^*$ and firms choose ERJV cartelization. As shown in Fig. 2, for firms to choose ERJV cartelization the government must increase the tax with respect to t^k, which reduces social welfare. In spite of this, social welfare is greater under ERJV cartelization.

To summarize, we find that the government chooses the tax that makes firms choose ERJV cartelization, the form of organizing their environmental R&D that generates the highest social welfare. This is because only under ERJV cartelization do firms cooperate in environmental R&D. As a result, the government is able to set the tax that makes firms choose this form of organizing environmental R&D.[22]

6. Conclusions

Empirical evidence shows that firms are increasingly concerned about Environmental Corporate Social Responsibility. Firms voluntarily take actions to reduce the impact of their activities on the environment beyond the requirements of law. Those actions include investments to develop advanced emission abatement technologies that improve the quality of the environment. Their investment in green technologies depends on whether they organize their R&D activities competitively or cooperatively, and on whether they disclose their knowledge to their rivals or not.

The literature on the environment has analyzed how firms organize R&D investments that reduce their pollutant emissions, assuming that they maximize profits. However, empirical evidence shows that firms are increasingly socially responsible. To fill this gap in the literature, this paper analyzes the choice by socially responsible firms of how to organize environmental R&D investments.

In this paper we consider that the objective function of firms incorporates the environmental damage that they generate as part of their social concern. Environmentally innovative firms can undertake pollution abatement innovation competitively or cooperatively and can decide how much of their knowledge to disclose. In addition, the regulator is able to credibly commit to an environmental policy instrument.

We find that firms' choice of how to organize environmental R&D depends on their level of environmental concern. If they are profit-maximizers or if their degree of social concern is low, firms' profits are the highest under ERJV cartelization. However, ERJV cartelization is not better than ERJV competition and R&D competition for larger values of environmental responsibility. If the degree is high enough, firms prefer ERJV competition to any other regime, while if the degree is intermediate firms prefer R&D competition. This paper also presents the environmental damage, consumer surplus, and welfare outcomes of different environmental R&D formations. We find that under ERJV cartelization social welfare is always higher and environmental damage lower than in the other two cases analyzed. The consumer surplus under ERJV cartelization is the highest for low and high values of environmental concern, but for intermediate environmental responsibility coefficients the consumer surplus is the highest under R&D competition.

The following facts and policy implications emerge from our analysis: Although ERJV cartelization is socially preferred, it is not always the first-choice R&D formation for firms. This discrepancy between social and private incentives arises when firms' concern about the environment is not low enough. Thus, when designing an appropriate environmental policy, the socially responsible behavior of firms should be taken into account.

We extend the model to consider that the government commits first to the environmental policy and then firms decide how to organize their environmental R&D. We find that the government chooses the tax that makes firms choose ERJV cartelization, the form of organizing their environmental R&D that generates the highest social welfare. Therefore, the government may use the environmental policy to shape firms' organization of environmental R&D activities.

In this paper we consider that the degree of social responsibility is exogenously given. To solve the model assuming that the degree of social responsibility internalized by firms is endogenously determined it would be necessary to modify the model, adding new assumptions and changing some of the existing ones. This would constitute a new paper, so we leave it for future work.

Declaration of Competing Interest

None.

Credit authorship contribution statement

All three authors have worked equally hard on the paper.

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Appendix A. Environmental R&D competition

Under R&D competition the equilibrium values of output, abatement levels, profits, emissions, consumer surplus, environmental damage and social welfare are as follows:

(i) If $\theta \leq 0.4729$:

$$q^n = \frac{2(A-c)(1+\theta)(3+\theta)\left(12+15\theta+4\theta^2\right)}{243+606\theta+540\theta^2+202\theta^3+27\theta^4}, z^n = \frac{3(A-c)\left(3+4\theta+\theta^2\right)^2}{243+606\theta+540\theta^2+202\theta^3+27\theta^4},$$

[22] The result obtained in this section is for $d = 1/2$. As parameter d increases, the government's interest in firms choosing ERJV competition becomes greater. This happens, for example, for $\theta > 0.2891$ if $d = 4$ and for $\theta > 0.1316$ if $d = 14$. Thus, as d increases the range of values of θ for which the government sets a tax such that firms choose ERJV competition becomes broader.

$$\pi^n = \frac{(A-c)^2(1+\theta)^2(3+\theta)^2\left(1233+3402\theta+3666\theta^2+1932\theta^3+497\theta^4+50\theta^5\right)}{2\left(243+606\theta+540\theta^2+202\theta^3+27\theta^4\right)^2}$$

$$e^n = \frac{(A-c)\left(45+114\theta+102\theta^2+38\theta^3+5\theta^4\right)}{243+606\theta+540\theta^2+202\theta^3+27\theta^4}, CS^n = \frac{8(A-c)^2(1+\theta)^2(3+\theta)^2\left(12+15\theta+4\theta^2\right)^2}{\left(243+606\theta+540\theta^2+202\theta^3+27\theta^4\right)^2},$$

$$ED^n = \frac{(A-c)^2(1+\theta)^2(3+\theta)^2\left(15+18\theta+5\theta^2\right)^2}{\left(243+606\theta+540\theta^2+202\theta^3+27\theta^4\right)^2}, W^n = \frac{2(A-c)^2(1+\theta)(3+\theta)\left(15+18\theta+5\theta^2\right)}{243+606\theta+540\theta^2+202\theta^3+27\theta^4}$$

(ii) If $\theta > 0.4729$:

$$q^n = \frac{(A-c)(1+\theta)^2(3+\theta)}{(3+2\theta)\left(3+6\theta+2\theta^2\right)}, z^n = \frac{(A-c)\theta(2+\theta)^2}{(3+2\theta)\left(3+6\theta+2\theta^2\right)}, e^n = \frac{(A-c)\left(3+3\theta+\theta^2\right)}{(3+2\theta)\left(3+6\theta+2\theta^2\right)}$$

$$\pi^n = \frac{(A-c)^2\left(18+102\theta+202\theta^2+198\theta^3+104\theta^4+28\theta^5+3\theta^6\right)}{2(3+2\theta)^2\left(3+6\theta+2\theta^2\right)^2}, CS^n = \frac{2(A-c)^2(1+\theta)^4(3+\theta)^2}{(3+2\theta)^2\left(3+6\theta+2\theta^2\right)^2}$$

$$ED^n = \frac{(A-c)^2\left(3+3\theta+\theta^2\right)^2}{(3+2\theta)^2\left(3+6\theta+2\theta^2\right)^2}, W^n = \frac{(A-c)^2\left(27+168\theta+345\theta^2+344\theta^3+181\theta^4+48\theta^5+5\theta^6\right)}{(3+2\theta)^2\left(3+6\theta+2\theta^2\right)^2}$$

Appendix B. ERJV competition

Under ERJV competition the equilibrium values of output, abatement levels, profits, emissions, consumer surplus, environmental damage, and social welfare are:

$$q^c = \frac{(A-c)(3+\theta)(54+23\theta)}{3\left(180+154\theta+33\theta^2\right)}, z^c = \frac{(A-c)\left(54+39\theta+7\theta^2\right)}{3\left(180+154\theta+33\theta^2\right)}, \quad e^c = \frac{3(A-c)\left(6+5\theta+\theta^2\right)}{180+154\theta+33\theta^2}$$

$$\pi^c = \frac{(A-c)^2(3+\theta)\left(20412+298808\theta+15099\theta^2+2983\theta^3+162\theta^4\right)}{18\left(180+154\theta+33\theta^2\right)^2},$$

$$CS^c = \frac{2(A-c)^2(3+\theta)^2(54+23\theta)^2}{9\left(180+154\theta+33\theta^2\right)^2}, ED^c = \frac{9(A-c)^2(2+\theta)^2(3+\theta)^2}{\left(180+154\theta+33\theta^2\right)^2}, W^c = \frac{2(A-c)^2(3+\theta)(36+17\theta)}{3\left(180+154\theta+33\theta^2\right)}.$$

Appendix C. ERJV cartelization

Under ERJV cartelization the equilibrium values of output, abatement levels, emissions, profits, consumer surplus, environmental damage, and social welfare are:

$$q^k = \frac{5(A-c)(3+\theta)(39+17\theta)}{1863+1626\theta+355\theta^2}, z^k = \frac{6(A-c)\left(36+27\theta+5\theta^2\right)}{1863+1626\theta+355\theta^2}, e^k = \frac{(A-c)\left(153+126\theta+25\theta^2\right)}{1863+1626\theta+355\theta^2}$$

$$\pi^k = \frac{(A-c)^2(3+\theta)\left(121851+182430\theta+92526\theta^2+17200\theta^3+625\theta^4\right)}{\left(1863+1626\theta+355\theta^2\right)^2},$$

$$CS^k = \frac{50(A-c)^2(3+\theta)^2(39+17\theta)^2}{\left(1863+1626\theta+355\theta^2\right)^2}, ED^k = \frac{(A-c)^2(3+\theta)^2(51+25\theta)^2}{\left(1863+1626\theta+355\theta^2\right)^2}, W^k = \frac{5(A-c)^2(3+\theta)(51+25\theta)}{1863+1626\theta+355\theta^2}.$$

Appendix D. Organization of environmental R&D

If the profits of firms shown in Appendixes A, B and C are compared, the following emerges.

$$\pi^k - \pi^c = (A-c)^2(3+\theta)\left(218166372+8684314556\theta+1225009176\theta^2-20861831076\theta^3-29338688706\theta^4-18535723386\theta^5-6282717756\theta^6-1114556956\theta^7 - 8164800\theta^8\right) \Big/ 18\left(180+154\theta+33\theta^2\right)^2\left(1863+1626\theta+355\theta^2\right)^2$$

Thus, $\pi^k > \pi^c$ if and only if $\theta < 0.5512$.
If $\theta \le 0.4729$:

$$\pi^k - \pi^n = (A-c)^2(3+\theta)\big(1551984867 + 5529577995\theta + 8198545541\theta^2 - 30049722387\theta^3 - 78138974862\theta^4 - 105345187686\theta^5 - 90608616810\theta^6 - 52956584586\theta^7 - 21391068933\theta^8 - 5901146421\theta^9 - 1063879987\theta^{10} - 113151075\theta^{11} - 5390000\theta^{12}\big)\Big/2\big(1863 + 1626\theta + 355\theta^2\big)^2\big(243 + 606\theta + 540\theta^2 + 202\theta^3 + 27\theta^4\big)^2$$

$$\pi^c - \pi^n = (A-c)^2(3+\theta)\big(126679788 + 433270944\theta - 93688865\theta^2 - 2556206829\theta^3 - 6353210241\theta^4 - 8342566749\theta^5 - 7019185239\theta^6 - 4019263347\theta^7 - 1591785363\theta^8 - 430726211\theta^9 - 76192236\theta^{10} - 7953444\theta^{11} - 371952\theta^{12}\big)\Big/18\big(180 + 154\theta + 33\theta^2\big)^2\big(243 + 606\theta + 540\theta^2 + 202\theta^3 + 27\theta^4\big)^2$$

Thus, $\pi^k > \pi^n$ if and only if $\theta < 0.3615$ and $\pi^c > \pi^n$ if and only if $\theta < 0.3548$.
If $\theta > 0.4729$:

$$\pi^k - \pi^n = (A-c)^2\big(-3254256 - 388323372\theta - 798042789\theta^2 - 268341669\theta^3 + 1036960569\theta^4 + 1742701089\theta^5 + 1372006439\theta^6 + 652090629\theta^7 + 197526469\theta^8 + 37585529\theta^9 + 4123259\theta^{10} + 200009\theta^{11}\big)\Big/2(3+2\theta)^2\big(3 + 6\theta + 2\theta^2\big)^2\big(1863 + 1626\theta + 355\theta^2\big)^2$$

$$\pi^c - \pi^n = (A-c)^2\big(-288684 - 3373812\theta - 6918615\theta^2 - 2287872\theta^3 + 9327519\theta^4 + 15980004\theta^5 + 12995766\theta^6 + 6452874\theta^7 + 2064504\theta^8 + 419040\theta^9 + 49429\theta^{10} + 2592\theta^{11}\big)\Big/18(3+2\theta)^2\big(3 + 6\theta + 2\theta^2\big)^2\big(180 + 154\theta + 33\theta^2\big)^2$$

Thus, $\pi^k > \pi^n$ if and only if $\theta > 0.7046$ and $\pi^c > \pi^n$ if and only if $\theta > 0.6913$.

Appendix E. Alternative timing

To simplify the presentation of the results we assume that $A = 1$ and $c = 0$. Taking into account the results in Section 3, in the fifth to third stages the following is obtained:

$$q^n(t) = \frac{(1-t+\theta)\big(3+4\theta+\theta^2\big)}{9+24\theta+18\theta^2+4\theta^3},\ a^n(t) = \frac{\theta(2+\theta)^2 + t\big(9+11\theta+3\theta^2\big)}{9+24\theta+18\theta^2+4\theta^3},\ q^c(t) = \frac{(3+\theta)(1-t+2\theta)}{9+24\theta+9\theta^2}$$

$$a^c(t) = \frac{\theta(2+\theta)+t(9+4\theta)}{9+24\theta+9\theta^2},\ q^k(t) = \frac{(3+\theta)(1-t+4\theta)}{9+42\theta+17\theta^2},\ a^k(t) = \frac{2(\theta(2+\theta)+t(9+4\theta))}{9+42\theta+17\theta^2}$$

$q^n(t) - a^n(t) > 0$ if $t < t^{nh} = \frac{3+3\theta+\theta^2}{12+15\theta+4\theta^2}$, $q^c(t) - 2a^c(t) > 0$ if $t < t^{ch} = \frac{1+\theta}{7+3\theta}$ and $q^k(t) - 2a^k(t) > 0$ if $t < t^{kh} = \frac{3+5\theta}{39+17\theta}$. As $t^{kh} < t^{ch} < t^{nh}$, we have to assume that $t < t^{kh}$ to ensure that the emission level of the firms is positive in all cases.

$$\pi^n(t) = \big(18 + 102\theta + 202\theta^2 + 198\theta^3 + 104\theta^4 + 28\theta^5 + 3\theta^6 - 2t\big(18 + 111\theta + 190\theta^2 + 143\theta^3 + 51\theta^4 + 7\theta^5\big) + t^2\big(99 + 552\theta + 961\theta^2 + 730\theta^3 + 251\theta^4 + 32\theta^5\big)\big)\Big/\Big(2\big(9 + 24\theta + 18\theta^2 + 4\theta^3\big)^2\Big)$$

$$W^n(t) = \big(27 + 168\theta + 345\theta^2 + 344\theta^3 + 181\theta^4 + 48\theta^5 + 5\theta^6 - t^2\big(243 + 606\theta + 540\theta^2 + 202\theta^3 + 27\theta^4\big) - 2t\big(-27 - 3\theta + 78\theta^2 + 86\theta^3 + 35\theta^4 + 5\theta^5\big)\big)\Big/\big(9 + 24\theta + 18\theta^2 + 4\theta^3\big)^2$$

$$\pi^c(t) = \Big(18 + 102\theta + 178\theta^2 + 106\theta^3 + 19\theta^4 - 2t\big(18 + 102\theta + 115\theta^2 + 32\theta^3\big) + t^2\big(261 + 1074\theta + 790\theta^2 + 162\theta^3\big)\Big)\Big/\Big(18\big(3 + 8\theta + 3\theta^2\big)^2\Big)$$

$$W^c(t) = \Big(9 + 56\theta + 97\theta^2 + 54\theta^3 + 9\theta^4 - t^2\big(180 + 154\theta + 33\theta^2\big) + t\big(36 + 26\theta - 10\theta^2 - 6\theta^3\big)\Big)\Big/\Big(3\big(3 + 8\theta + 3\theta^2\big)^2\Big)$$

$$\pi^k(t) = \Big(9 + 87\theta + 239\theta^2 + 173\theta^3 + 34\theta^4 - 2t\big(9 + 105\theta + 161\theta^2 + 51\theta^3\big) + t^2\big(171 + 1635\theta + 1343\theta^2 + 289\theta^3\big)\Big)\Big/\big(9 + 42\theta + 17\theta^2\big)^2$$

$$W^k(t) = \Big(27 + 300\theta + 839\theta^2 + 554\theta^3 + 100\theta^4 - t^2\big(1863 + 1626\theta + 355\theta^2\big) + t\big(216 + 246\theta - 52\theta^2 - 50\theta^3\big)\Big)\Big/\big(9 + 42\theta + 17\theta^2\big)^2$$

Comparing the profits obtained by firms in the three cases, we obtain the following:

$$\pi^c(t) - \pi^n(t) = \big(2t\theta\big(729 + 7047\theta + 22437\theta^2 + 33453\theta^3 + 27540\theta^4 + 13560\theta^5 + 4077\theta^6 + 707\theta^7 + 55\theta^8\big) + \theta^2\big(972 + 7776\theta + 23733\theta^2 + 36594\theta^3 + 32151\theta^4 + 16818\theta^5 + 5182\theta^6 + 868\theta^7 + 61\theta^8\big) + t^2\big(13122 + 112266\theta + 373491\theta^2 + 640872\theta^3 + 629532\theta^4 + 367380\theta^5 + 125841\theta^6 + 23358\theta^7 + 1813\theta^8\big)\big)\Big/\Big(18(3+2\theta)^2\big(3 + 6\theta + 2\theta^2\big)^2\big(3 + 8\theta + 3\theta^2\big)^2\Big) > 0 \text{ for all } t \text{ and } \theta.$$

$$\pi^k(t) - \pi^c(t) = (3+\theta)(\theta(2+\theta) + t(9+4\theta))\big(\theta\big(-270 - 1323\theta - 1623\theta^2 - 449\theta^3 + 17\theta^4\big) + t\big(243 + 4563\theta + 13689\theta^2 + 9489\theta^3 + 1904\theta^4\big)\big)\Big/\Big(18\big(3 + 8\theta + 3\theta^2\big)^2\big(9 + 42\theta + 17\theta^2\big)^2\Big) > 0 \text{ if and only if } t > t^*, \text{ with } t^* = \frac{\theta\big(270 + 1323\theta + 1623\theta^2 + 449\theta^3 - 17\theta^4\big)}{243 + 4563\theta + 13689\theta^2 + 9489\theta^3 + 1904\theta^4}.$$

Thus, $\pi^k(t) > \pi^c(t)$ if $t > t^*$, $\pi^k(t) < \pi^c(t)$ if $t < t^*$ and $\pi^k(t) = \pi^c(t)$ if $t = t^*$.

$$W^k(t) > W^c(t) \text{ if } t < t^W = \frac{108 + 522\theta + 711\theta^2 + 635\theta^3 + 405\theta^4 + 99\theta^5}{1323 + 5031\theta + 3681\theta^2 + 785\theta^3 + 12\theta^4}, \text{ where } t^W > t^*$$

As seen in Section 3, the tax maximizing $W^k(t)$ is $t^k = \frac{(108+123\theta-26\theta^2-25\theta^3)}{1863+1626\theta+355\theta^2}$, so $W^k(t^k) = W^k = \frac{5(3+\theta)(51+25\theta)}{1863+1626\theta+355\theta^2}$. The tax that maximizes $W^c(t)$ is $t^c = \frac{(2-\theta)(9+11\theta+3\theta^2)}{180+154\theta+33\theta^2}$, so $W^c(t^c) = W^c = \frac{2(3+\theta)(36+17\theta)}{3(180+154\theta+33\theta^2)}$. In addition, if $t = t^*$ the following is obtained:

$$W^k(t^*) = (19683 + 9491158\theta + 112863778\theta^2 + 521521174\theta^3 + 1090428848\theta^4 + 1075841146\theta^5 + 535988870\theta^6 + 131313554\theta^7 + 12596450\theta^8) \Big/ (243 + 4563\theta + 136890\theta^2 + 94890\theta^3 + 19040\theta^4)^2$$

$$W^c(t^*) = (19683 + 8441820\theta + 109364580\theta^2 + 519188940\theta^3 + 1074682080\theta^4 + 1049804820\theta^5 + 519728220\theta^6 + 126886980\theta^7 + 12152450\theta^8) \Big/ (243 + 4563\theta + 136890\theta^2 + 94890\theta^3 + 19040\theta^4)^2$$

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