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Summary

We explore the interplay of competition and environmental policies to address the question of whether green antitrust has beneficial effects in terms of both environmental and consumer welfare performance. We focus on two environmental policy tools, an emission tax and an emission standard, and explore three particular configurations: competitive 'green R&D, collaborative 'green' R&D in the form of a joint lab, and the benchmark case of no 'green' R&D. Firms compete in the product market by selling a homogeneous product, either by setting prices (Bertrand competition) or quantities (Cournot competition) while facing convex costs. We show that 'green antitrust' can unambiguously improve the effectiveness of environmental policy without undermining the interests of either consumers or producers, establishing a 'win-win-win' outcome.

Keywords: 'Green' R&D, emission tax, environmental standard, 'green' antitrust, R&D cooperation, joint lab, convex costs

JEL Classification: L13, L4, Q55, Q58

Corresponding Author
Joanna Poyago-Theotoky
Department of Economics
University of Salento
Centro Ecotekne Pal. C - S.P. 6 - 73100 Lecce
joanna.poyago-theotoky@unisalento.it

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Marie-Laure Cabon-Dhersin[*], Joanna Poyago-Theotoky[†], Natacha Raffin[‡]

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Abstract

We explore the interplay of competition and environmental policies to address the question of whether green antitrust has beneficial effects in terms of both environmental and consumer welfare performance. We focus on two environmental policy tools, an emission tax and an emission standard, and explore three particular configurations: competitive 'green R&D, collaborative 'green' R&D in the form of a joint lab, and the benchmark case of no 'green' R&D. Firms compete in the product market by selling a homogeneous product, either by setting prices (Bertrand competition) or quantities (Cournot competition) while facing convex costs. We show that 'green antitrust' can unambiguously improve the effectiveness of environmental policy without undermining the interests of either consumers or producers, establishing a 'win-win-win' outcome.

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[*]University of Rouen Normandie, LERN UR 4702, F-76000 Rouen, France.
https://orcid.org/0000-0002-9295-309X
e-mail: marie-laure.cabon-dhersin@univ-rouen.fr

[†]University of Salento, Department of Economics, Ecotekne, Lecce 73100, Italy and The Australian National University, Research School of Economics, Canberra, ACT 2601, Australia.
https://orcid.org/0000-0003-2957-6612
e-mail: joanna.poyago-theotoky@unisalento.it and joanna.poyago-theotoky@anu.edu.au

[‡]ENS Paris-Saclay, CEPS, 4 avenue des sciences, 91190 Gif-sur-Yvette, France.
https://orcid.org/0000-0001-7279-4119
e-mail: natacha.raffin@ens-paris-saclay.fr

1 Introduction

Economic policy towards the environment is of paramount and increasing importance given the challenges faced by climate change, pollution and climate-related inequality. Several environmental policy instruments are being used, including market-based tools, such as emission taxes or tradable permits, as well as command-and-control tools, such as standards. At the same time, in the realm of competition policy and antitrust, there have been changes in the way that collaboration amongst firms in 'green' innovation and abatement activities is viewed. In several jurisdictions, including the EU, UK, Japan and Australia,[1] competition policy now has a broader view which clearly includes environmental concerns. This is the notion of 'green' antitrust: competition policy towards firms collaborating to achieve environmental and sustainable outcomes is more permissive, indeed such collaboration is treated more leniently.

In this paper, we explore the interplay of competition and environmental policies and ask whether 'green' antitrust has beneficial effects in terms of both environmental and consumer welfare performance (a topical and open question, Inderst and Thomas (2023)). We do so by focussing on two widely used environmental policy tools: an emission tax and an emissions cap (standard),[2] and examine three distinct configurations: (i) a benchmark where firms do not engage in 'green' R&D to control emissions, (ii) a competitive R&D scenario and (iii) a cooperative R&D scenario where firms operate a joint lab and share the costs of 'green' R&D. We focus on the joint lab as the organisational structure of cooperative R&D as opposed to other forms such as research joint ventures, research cartels etc. as we wish to avoid issues related to the sharing of information across different labs and associated spillovers.[3] In addition, the joint lab is often used in practice by firms but nevertheless is less well researched.

We further abstract from issues of policy credibility, assuming a committed regulator.[4] However, to address the effectiveness of 'green' antitrust, we focus on strategic markets, where competing firms faced with environmental regulation must undertake abatement and may further engage in 'green' innovation to further ameliorate their environmental footprint and reduce regulatory costs. More importantly, we consider

[1]For details see: The European Commission (2023), Competition and Markets Authority (2023), Japan Fair Trade Commission (2023) and Australian Competition and Consumer Commission (2025). For the U.S. see Hearn et al. (2023); in general there is no green exemption and traditional consumer-welfare analysis dominates.

[2]See Requate (2005) for an excellent survey on the relative merits of several regulatory instruments in oligopolistic markets.

[3]See Espinola-Arredondo et al. (2026) for a survey on green innovation and the role of spillovers.

[4]The issues that can arise from non-credibility (time-consistency) of the regulator, although interesting, are outside the scope of the present analysis.

different organisational setups with regards to firms conduct in both output/pricing and R&D choices.

The modelling approach we follow stipulates that, at the outset, the regulator sets the environmental policy tool, an emission tax or a cap on emissions. We then distinguish between a benchmark setup, where firms do not engage in 'green' innovation but compete in the product market either by setting prices (Bertrand competition) or quantities (Cournot competition). Next, we allow firms to conduct 'green' R&D, followed by their choice of output or price, respectively. In this instance, the relevant market configurations entail full competition or collaboration in the form of a joint lab (where firms collaborate in R&D only and share costs fully).

Firms produce homogeneous goods that generate pollution and are faced with convex abatement and 'green' innovation costs. Interestingly, in the case of price (Bertrand) competition, where we adopt an original approach to obtain the equilibrium solution, we find that the outcome is 'win-win-win', in the sense of a stricter environmental standard, increased firm profitability and better welfare performance, when firms collaborate in a joint lab relative to R&D competition. The joint lab also results in lower pollution emissions, when an emission tax is implemented. In contrast, when firms compete in quantities (Cournot), the extent of environmental damage as well as the effectiveness of 'green' R&D are crucial in ranking the performance of the organisational setups. We find that for relative large environmental damage and less effective R&D, the joint lab performs better in terms of emissions (stricter regulation), 'green' R&D (higher), profitability and welfare, relative to full competition, with the ranking reversed for relatively contained damages.

The results we obtain reveal that the joint lab, in general, outperforms the other configurations, i.e., full R&D competition and the benchmark case where there is no 'green' innovation. This is a rather strong finding, which highlights the importance for policy makers in pursuing 'green antitrust', and advocates for the relaxation of competition policy to promote higher welfare, less pollution and stronger incentives for firms to innovate.

1.1 Related Literature

The paper contributes to three branches of the literature. First, we follow the literature analysing emission standards and emission taxes such as Montero (2002); Moner-Colonques and Rubio (2016); Amir et al. (2018); Gama (2020); Amir et al. (2023) and Cabon-Dhersin and Raffin (2024). We enrich these papers by distinguishing between

standard abatement activities and 'green' R&D that leads to further abatement. Second, we further explore different organization scenarios for the conduct of 'green' R&D, introducing the case of a joint lab and consider the potential benefits of 'green' antitrust. Studies with a similar scope include Poyago-Theotoky (2007), under emission taxes only, and Cabon-Dhersin and Raffin (2024) where emission taxes and standards are considered; but only comparing competition with a research joint venture. Third, we contribute to the analysis of Bertrand competition with homogeneous goods and convex costs in the context of environmental innovation, by introducing the methodology pioneered by Dastidar (1995, 2001) and further developed by Cabon-Dhersin and Drouhin (2014, 2020). To the best of our knowledge, this is the first paper studying price competition with homogeneous goods within the context of environmental and competition policy.

The paper is organized as follows: In section 2 we present the basic structure of the model, then in section 3 we analyse the case with Bertrand competition, in section 4 we present the case with Cournot competition and in section5 we provide some concluding remarks. We relegate all proofs in the Appendix.

2 The Model Basics

We consider a duopoly market where two ex-ante symmetric and profit maximizing firms, indexed i and j, with $i, j = 1, 2$ and $i \neq j$, compete either in prices (Bertrand competition) or in quantities (Cournot competition) by selling a homogeneous good. To simplify, and without loss of generality, the demand is linear, $D(p) = 1 - p$, where p is the market price with associated inverse demand function $p(Q) = 1 - Q$, where $Q = q_i + q_j$ is the aggregate output while production takes place under constant returns to scale, and is assumed costless.

Production of the good results in pollution. Firms are therefore subject to environmental regulation, which takes the form of either (i) an endogenous environmental tax t on emissions or (ii) a standard, i.e., a cap on emissions $\bar{e}$. Hence firms abate emissions either to alleviate the burden of the tax or to comply with the standard. They can do this by investing in standard abatement activities[5] or, they could invest in specific 'green' R&D which will allow for a more efficient production process as well as reduce emissions further. This approach differs from the related literature as we explicitly distinguish between two types of decision: abatement activity and 'green' R&D.[6] Such a

[5]This represents end-of-pipe type abatement.

[6]In a way, think about abatement as mitigation and 'green' R&D as a form of adaptation.

modelling choice is motivated by timing considerations since innovation usually precedes abatement/compliance decisions, as well as empirical observation.

Following Petrakis and Xepapadeas (1999), Poyago-Theotoky (2007) and Ulph (1996), after an appropriate choice of measurement units such that each unit of output generates one unit of pollution, we express firm i's (net) emissions as $e_i = q_i - a_i$, in the case a tax is implemented and firms can freely choose their emissions, where a_i is the level of abatement. When a standard is implemented, abatement activities are mechanically driven by the environmental policy, $\bar{e}$, so net emissions are simply $\bar{e} = q_i - a_i$ with $a_i = q_i - \bar{e}$. When firms engage in 'green' R&D (net) emissions become $e_i = q_i - a_i - z_i$, where z_i denotes 'green' R&D, so effectively firm i is reducing its (standard) abatement level. Next we consider the costs associated with abatement and 'green' R&D.

Abatement entails a convex cost: $c_i(a_i) = \frac{\lambda}{2}a_i^2$, where $\lambda > 0$ is a measure of the efficiency of abatement technology. Abatement expenditure is a variable cost, varying with a firm's production and implying that, for a given level of emissions, the higher a firm's production, the higher its marginal abatement cost. The 'green' R&D expenditure, denoted by $c_i(z_i)$, is also convex, and given by $c_i(z_i) = \frac{\gamma}{2}z_i^2$, where $\gamma > 0$ captures the effectiveness of 'green' R&D: the higher the γ, the less effective is the innovation process and vice versa.

The regulator maximises a standard social welfare function, composed of the sum of consumers' surplus (CS), producers' surplus (PS), emission tax revenue (T) –whenever a tax is implemented– minus environmental damage (ED):

$$SW = CS + PS(+T) - ED, \tag{1}$$

where $CS = \frac{1}{2}(q_i + q_j)^2$, $PS = \pi_i + \pi_j$ and $ED = \frac{d}{2}(e_i + e_j)^2$. The parameter $d > 1$ is proportional to marginal damage (it captures the severity of damage).[7]

In the sequel, we consider three different scenarios/games: In the first, the *Benchmark* case (B), there is no 'green' R&D. The regulator sets the level of the environmental policy, emission tax or standard. When the policy instrument in the first stage is a tax, then in the second stage firms choose their emissions. When the regulator implements an environmental standard, the second stage vanishes, as firms have to comply with the cap set on emissions ($\bar{e}$). In the final stage, firms compete in the market. The second scenario introduces 'green' R&D with firms setting their R&D independently in the first stage while the regulator sets the emission tax or standard: *Competition* (C). The third

[7]In the case of an environmental standard, polluting emissions are in fact equal to the cap on emissions set by the regulator, so that the environmental damage becomes: $ED = \frac{d}{2}(2\bar{e})^2$.

scenario considers cooperation in 'green' R&D in the form of a joint laboratory: *Joint Lab* (J). In this instance, in the first stage the regulator sets the level of the policy instrument while firms choose their R&D jointly. In both C and J the next stages are the same as in the *Benchmark* case. We denote each of the three distinct configurations, by the superscript h, where $h \in \{B, C, J\}$. The solution concept is subgame perfect Nash equilibrium (SPNE), hence we solve these games backward. In the following section, we focus on price competition (*Bertrand*), and subsequently we examine competition in quantities (*Cournot*).

3 Bertrand Competition

First we derive the equilibrium prices, independently of the environmental regulation type. Then, we explicitly introduce the environmental policy tool, as a form of a tax or a standard. We then obtain equilibrium results for the market competition stage, presented in Proposition 1.

3.1 Equilibrium prices

In the standard textbook case of Bertrand competition, firms sell a homogeneous good and unit costs are constant so that each firm's production is required to meet its demand, D_i, resulting in a discontinuous function of its price: when both firms set the same price, they equally share total demand, whereas the firm setting the lowest price serves the entire market. This generates the standard "price war" that leads to marginal cost pricing (and zero profits).

However, in the setting we consider, this is not the case: the quadratic abatement cost function depends on the output of the firm that satisfies the demand at the lowest price. Therefore, to find a solution to the pricing stage, we adapt the approach developed by Dastidar (1995, 2001) and further extended by Cabon-Dhersin and Drouhin (2014, 2020). When firms face convex costs and are committed to satisfying demand, Bertrand competition yields a continuum of prices above the competitive price as Nash equilibria in pure strategies. By lowering its price, firm i increases its revenue by producing more (thus increasing emissions), which involves even higher abatement costs (which are convex in the level of output) potentially making this deviation in price non-profitable. Due to the convexity of abatement costs, there exists a critical price $\bar{p}$ (higher than the price for which profit is zero) above which unilateral price undercutting is not profitable, and hence the "price war" does not occur.

Let p_L be the lowest price the rival firm, j selects. For a given level of net emissions, if firm j selects the lowest price, p_L, then firm i does not serve the market at all. The absence of production and induced polluting emissions imply that abatement costs vanish, as well the burden of the tax when applicable so that $\pi_i(p_i) = 0$ (in the *Benchmark* case). When firms engage in 'green' R&D (cases C and J), firm i incurs sunk costs related to R&D: $c_i(z_i)$, so that its profit becomes $\pi_i(p_i) = -c_i(z_i)$. When firm i also quotes the lowest price, p_L, then it is active and earns profits $\hat{\pi}_i(p, m)$, with $m = 1, 2$ the number of active firms in the market. The above is summarised below:

$$\pi_i(p_i) = \begin{cases} 0 \text{ or } -c_i(z_i) & \text{if } p_i > p_L \\ \hat{\pi}_i(p, m) & \text{if } p_i = p_L = p \end{cases} \tag{2}$$

The difference $\hat{\pi}_i(p, 1) - \hat{\pi}_i(p, 2)$ can be interpreted as the incentive for a firm to undercut the market price p. This incentive vanishes when

$$\hat{\pi}_i(p, 1) - \hat{\pi}_i(p, 2) = 0 \tag{3}$$

The above equality yields a critical price $\bar{p}$, corresponding to the price at which each firm is indifferent between serving the entire market as a monopolist and sharing the market with its rival. This price must necessarily be higher than the price for which the variable part of the profit is zero, $p_{\min}$.

Cabon-Dhersin and Drouhin (2014, 2020) have shown how this price, $\bar{p}$, can be selected from a continuum of equilibrium prices (in pure strategies) ranging from the minimum price $p_{\min}$ up to $\bar{p}$, using either a payoff-dominance criterion or the selection of a SPNE of a two-stage game. Following Dastidar (1995), they analyse a two-stage game in which a choice of 'soft' capacity is made in the first stage before price competition is resolved in the second stage. The setting in the present paper satisfies similar properties, where firms choose their investment in 'green' R&D in the first stage and then compete in prices. As a consequence, we build on Cabon-Dhersin and Drouhin (2014, 2020) to establish that $\bar{p}$ is indeed the price equilibrium in the SPNE. Furthermore, the (implicit) collusive price is defined as:

$$p^{col} \equiv \arg\max \{\hat{\pi}_i(p, 2)\} \tag{4}$$

and can emerge as the SPNE of the multi-stage game if and only if this collusive price belongs to the equilibrium price interval $[p_{min}, \bar{p}]$. In particular, this will occur when

the convexity of the cost function is sufficiently strong (high values of λ.)

Next we compute the possible equilibrium prices $\bar{p}$ and p^{col} under the three different scenarios: the benchmark case (B), competitive 'green' R&D (C), and cooperative 'green' R&D, i.e., the joint lab (J). In addition, we now explicitly distinguish the environmental tax from the environmental standard.

3.2 Equilibrium analysis with an environmental tax

Each firm pays a per unit emission tax t for emissions it fails to abate. When two firms are active, the individual profit function of firm i is written, for any $z_i \geq 0$ and all $h \in \{B, C, J\}$ as:

$$\pi_i^h(p_i^h, z_i^h, e_i^h, t^h) = p_i^h \frac{D(p_i^h)}{2} - \frac{\lambda}{2}\left(\frac{D(p_i^h)}{2} - z_i^h - e_i^h\right)^2 - \frac{\gamma}{2}{z_i}^{h2} - t^h e_i^h. \quad (5)$$

Conditional on e_i^h, t^h and z_i^h, we solve the last stage by computing the equilibrium prices in all three scenarios.

3.2.1 Third stage: equilibrium prices

Benchmark Case: $h = B$ and $z_i = z_j = 0$

First we compute the critical price $\bar{p}_i(e_i)$ at which firm i is indifferent to operating in the market alone or with its rival. From equation (3):

$$p_i \frac{D(p_i)}{2} - \frac{\lambda}{2}\left(\frac{D(p_i)}{2} - e_i\right)^2 - te_i = p_i D(p_i) - \frac{\lambda}{2}\left(D(p_i) - e_i\right)^2 - te_i$$

After some algebraic manipulation, we obtain

$$\bar{p}_i^B(e_i) = \frac{\lambda(3 - 4e_i)}{4 + 3\lambda} \quad (6)$$

and

$$\bar{q}_i^B(e_i) = \frac{D(\bar{p}_i^B)}{2} = \frac{2(1 + \lambda e_i)}{4 + 3\lambda}. \quad (7)$$

Using the definition of the collusive price, (4), we find

$${p_i}^{col\,B}(e_i) = \frac{2 + \lambda(1 - 2e_i)}{4 + \lambda} \quad (8)$$

and

$$q_i{}^{col\,B}(e_i) = \frac{1+\lambda e_i}{4+\lambda}. \tag{9}$$

Note that for $\lambda = 4$, the price $\bar{p}$ (equation (6)) coincides with the collusive price, p^{col}, (equation (8)) for a given emissions level e_i. In addition, these prices are higher the lower the emissions.[8]

'Green' R&D - Competition and Joint-Lab: $h = C, J$ *and* $z_i, z_j > 0$

Using (5) together with equations (3) and (4), we obtain the prices $\bar{p}_i^h$, $p_i{}^{col\,h}$ and the associated output levels. Conditional on net emissions and the level of 'green' R&D effort, outputs $\bar{q}_i^h$ and $q_i{}^{col\,h}$ at this stage are identical under competitive and cooperative R&D. In particular, for $h = C, J$:

$$\begin{cases} \bar{p}_i^h(e_i^h, z_i^h) = \bar{p}_i^B(e_i^h) - \frac{4\lambda}{4+3\lambda} z_i^h, \\ \bar{q}_i^h(e_i^h, z_i^h) = \bar{q}_i^B(e_i^h) + \frac{2\lambda}{4+3\lambda} z_i^h \end{cases} \tag{10}$$

and

$$\begin{cases} p_i{}^{col\,h}(e_i^h, z_i^h) = p_i{}^{col\,B}(e_i^h) - \frac{2\lambda}{4+\lambda} z_i^h, \\ q_i{}^{col\,h}(e_i^h, z_i^h) = q_i{}^{col\,B}(e_i^h) + \frac{\lambda}{4+\lambda} z_i^h. \end{cases} \tag{11}$$

Notice that the prices when firms undertake 'green' R&D are directly compared to the benchmark case: in particular, for given net emissions, investing in 'green' R&D yields lower prices and higher production levels.

From now on, we focus on a symmetric equilibrium so that $e_i^h = e_j^h = e^h$ and $z_i^h = z_j^h = z^h$ for $i \neq j$.[9] Next, we consider the ranking of $p^{col\,h}$ and $\bar{p}^h$ for all $h = \{B, C, J\}$. This ranking is crucial in order to understand how an equilibrium price is selected at pricing stage. The following Lemma describes this.

Lemma 1. *In the last stage of the game, under all scenarios (*$h \in \{B, C, J\}$*), and for*

[8] This confirms the intuition that consumer surplus deteriorates with binding environmental regulations.

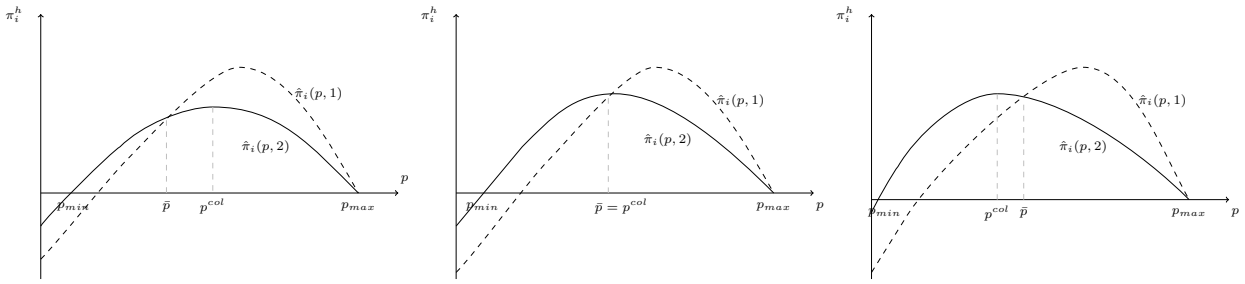
[9] At this stage of the game, we can assume symmetry since these choices by firms do not depend on their rival's choice.

given emissions, e^h, and 'green' R&D, $z^h \geq 0$,

$$\begin{cases} \textit{if } \lambda < 4, \quad \bar{p}^h(e^h, z^h) \quad \textit{is a payoff-dominant Nash equilibrium,} \\ \textit{if } \lambda > 4, \quad p^{col\,h}(e^h, z^h) \quad \textit{is a payoff-dominant Nash equilibrium,} \\ \textit{if } \lambda = 4, \quad \bar{p}^h = p^{col\,h} \quad \textit{is a payoff-dominant Nash equilibrium.} \end{cases}$$

Proof. See Appendix A. □

Whether the (implicitly) collusive price, $p^{col\,h}$, is lower or higher than the critical price $\bar{p}$ is pivotal for the resolution of the pricing stage, and depends on the relative magnitude of abatement costs. When abatement costs are slightly convex or, when the abatement technology is more efficient ($\lambda < 4$), the collusive price cannot be sustained, as it lies outside the equilibrium price interval. Therefore, firms set the critical price $\bar{p}$, which yields the highest attainable profit among all equilibrium prices. This case is illustrated in Figure 1(a). By contrast, when abatement costs are sufficiently convex or, when the abatement technology is less efficient ($\lambda > 4$), the collusive price is lower than $\bar{p}$. In this case, the collusive price belongs to the equilibrium price interval $[p_{\min}, \bar{p}]$ and can therefore be sustained as a final stage equilibrium. This configuration is illustrated in Figure 1 (c). Finally, the critical price $\bar{p}$ and the collusive price coincide when $\lambda = 4$ (see Figure 1(b)). In this case, $\bar{p}^h = p^{col\,h}$ is the payoff-dominant equilibrium price.



(a) $\lambda < 4$ (b) $\lambda = 4$ (c) $\lambda > 4$

Figure 1: Profit functions, $\hat{\pi}_i(p, m)$, given $e^h > 0$ and $z^h \geq 0$ for all $h \in \{B, C, J\}$.

Inserting equations (10) and (11) into equation (5), we obtain the individual firm reduced-form profit functions, for given e^h, t^h and $z^h \geq 0$:

$$\pi_i(e^h, z^h, t^h) = \begin{cases} \lambda(\bar{q}^h(e^h, z^h))^2 - \frac{\lambda}{2}\left(e^h + z^h\right)^2 - c_i(z^h) - t^h e^h & \text{if } \lambda \leq 4, \\ (2 + \frac{\lambda}{2})(q^{col\,h}(e^h, z^h))^2 - \frac{\lambda}{2}\left(e^h + z^h\right)^2 - c_i(z^h) - t^h e^h & \text{if } \lambda \geq 4 \end{cases} \tag{12}$$

which we next use in solving the emissions setting stage.

3.2.2 Second stage: polluting emissions

At the second stage, for $t^h = t$ and $z^h = z$, firms choose how much to pollute. They maximise profit, as given by (12)), by choosing their emissions e, i.e., the emissions they choose not to abate.[10]

Benchmark Case: $h = B$ and $z_i = z_j = 0$

Performing the maximisation, we obtain:

$$e^B(t) = \begin{cases} \frac{-t}{\lambda} + \frac{8\lambda(1-t)}{16+\lambda(24+\lambda)} & \text{if } \lambda \leq 4, \\ \frac{\lambda - t(4+\lambda)}{4\lambda} & \text{if } \lambda \geq 4. \end{cases} \tag{13}$$

'Green' R&D - Competition and Joint-Lab: $h = C, J$ and $z_i, z_j > 0$

When firms invest in 'green' R&D, the relevant profit maximisation yields:

$$e^h(t^h, z^h) = \begin{cases} e^B(t^h) - z^h & \text{if } \lambda \leq 4, \\ e^B(t^h) - z^h & \text{if } \lambda \geq 4 \end{cases} \tag{14}$$

As expected, the higher the tax rate, the lower the remaining emissions. In addition, 'green' innovation leads to lower emissions relative to the benchmark case. Consistently, we also notice that remaining emissions are identical in both scenarios $h = C, J$ for given tax and R&D effort.

3.2.3 First stage: environmental policy (tax) and 'green' R&D

At the first stage, the regulator chooses the emission tax that maximises social welfare while firms simultaneously choose their 'green' R&D, in scenarios C and J.

Benchmark Case: $h = B$ and $z_i = z_j = z^B = 0$

[10]The second-order conditions are always satisfied and this holds for the remainder of the paper.

The expression for social welfare (1), using expressions (12) and (13) for $z^B = 0$, can be written as:

$$SW^B(t^B) = \begin{cases} 2(1+\lambda)(\bar{q}^B(e^B(t^B)))^2 - (\lambda+2d)(e^B(t^B))^2 & \text{if } \lambda \leq 4, \\ (6+\lambda)(q^{col\,B}(e^B(t^B)))^2 - (\lambda+2d)(e^B(t^B))^2 & \text{if } \lambda \geq 4. \end{cases} \tag{15}$$

The regulator sets the environmental tax that maximises the above expression (indicated by superscript *), given by

$$t^{B*} = \begin{cases} \frac{8\lambda^2(2d-1)}{D^B} & \text{if } \lambda \leq 4, \\ \frac{2\lambda(d(4+\lambda)-\lambda)}{D^{B\prime}} & \text{if } \lambda \geq 4, \end{cases} \tag{16}$$

where $D^B = 2d(4+3\lambda)^2 + \lambda(16+\lambda(16+\lambda)) > 0$ and $D^{B\prime} = 2d(4+\lambda)^2 + 2\lambda(8+\lambda) > 0$. Inserting the equilibrium values of t^{B*} into equations (7), (9) and (13), we obtain equilibrium emissions and quantities for each firm:

$$e^{B*} = \begin{cases} \frac{8\lambda(1+\lambda)}{D^B} & \text{if } \lambda \leq 4, \\ \frac{\lambda(6+\lambda)}{D^{B\prime}} & \text{if } \lambda \geq 4 \end{cases} \tag{17}$$

$$q^{B*} = \begin{cases} \frac{2(2d+\lambda)(4+3\lambda)}{D^B} & \text{if } \lambda \leq 4, \\ \frac{(2d+\lambda)(4+\lambda)}{D^{B\prime}} & \text{if } \lambda \geq 4. \end{cases} \tag{18}$$

Using these equilibrium values we can calculate the SPNE individual profits, π^{B*}, and social welfare, SW^{B*}. All SPNE values are reported Tables 1 and 2 in Appendix (D).

'Green' R&D - Competition and Joint-Lab: $h = C, J$ and $z_i, z_j > 0$

When firms compete in the first stage, they choose the level of 'green' R&D that maximizes their individual profit (see equation (12)), given the tax t. The output levels $\bar{q}^C$ and $q^{col\,C}$ as well as emissions are given by expressions (10), (11) and (14). Performing the relevant profit maximization we obtain the 'green' R&D efforts conditional on t, for any value of $\lambda > 0$:

$$z^C(t^C) = \frac{t^C}{\gamma}. \tag{19}$$

In the case of cooperative R&D, the two firms set up a common joint lab to conduct

'green' R&D and share the associated costs equally. In particular, each firm enjoys an abatement cost reduction of z^J by spending $c_i(z^J) = \frac{\gamma}{4}(z^J)^2$. Given cooperation in R&D setting, this means that each firm maximizes joint profits, $\pi_i + \pi_j$ with respect to z^J, given the environmental tax t. Accordingly, we obtain the level of 'green' R&D conditional on the environmental tax for all $\lambda > 0$:

$$z^J(t^J) = \frac{2t^J}{\gamma}. \tag{20}$$

The regulator sets the environmental tax that maximises social welfare, and for $h = C, J$, this is given by

$$SW^h(t^h, z^h) = \begin{cases} 2(1+\lambda)(\bar{q}^h(e^h(t^h, z^h)))^2 - (\lambda + 2d)(e^h(t^h, z^h))^2 - (\gamma + \lambda)(z^h)^2 - 2z^h e^h(t^h, z^h) & \text{if } \lambda \leq 4, \\ (6+\lambda)(q^{col^h}(e^h(t^h, z^h)))^2 - (\lambda + 2d)(e^h(t^h, z^h))^2 - (\gamma + \lambda)(z^h)^2 - 2z^h e^h(t^h, z^h) & \text{if } \lambda \geq 4 \end{cases} \tag{21}$$

We then obtain the optimal tax rate, conditional on 'green' innovation:

$$t^h(z^h) = \begin{cases} t^{B*} - \frac{2d\lambda(16+\lambda(24+\lambda))}{D^B} z^h & \text{if } \lambda \leq 4, \\ t^{B*} - \frac{8\lambda(4+\lambda)}{D^{B'}} z^h & \text{if } \lambda \geq 4. \end{cases} \tag{22}$$

Expressions (21) and (22) above are the best-response functions for the regulator and firms respectively. Solving these simultaneously yields, for $h = C, J$, the optimal tax and 'green' R&D efforts as well as the remaining SPNE outcomes, namely e^{h*}, q^{h*}, π^{h*} and SW^{h*}, which are reported in Tables 1 and 2 in Appendix D.

This concludes the analysis under an emission tax.

3.3 Equilibrium analysis with an environmental standard

When the two firms are active in the market, the individual profit function of firm i, for any $z_i \geq 0$, can be written as:

$$\pi_i^h(p_i^h, z_i^h, \bar{e}^h) = p_i^h \frac{D(p_i^h)}{2} - \frac{\lambda}{2}\left(\frac{D(p_i^h)}{2} - z_i^h - \bar{e}^h\right)^2 - \frac{\gamma}{2} {z_i}^{h2}. \tag{23}$$

We then perform a similar analysis as in the previous section and distinguish the three different configurations, B, C and J. Given the profit function, (23), the last (pricing) stage yields similar results as in the case of the emission tax. Therefore, equilibrium

prices and outputs are identical, given by equations (6), (7), (8), (9), (10) and (11), for $e_i = \bar{e}$. As a direct consequence, Lemma 1 applies. Moreover, whenever the regulator chooses to implement a standard and since we assume that firms comply with the environmental objective, the remaining emissions to be abated exactly amount to $q_i - z_i - \bar{e}$ (for any $z_i \geq 0$). Effectively firms do not choose anymore their net emissions and this mechanically leads to the first stage of the game.

In the first stage, the regulator sets the environmental standard (emissions cap) by maximizing social welfare while firms simultaneously choose their 'green' R&D, in scenarios C and J. Hence, in the relevant expressions for social welfare (see (15) and (21)), $\bar{e}$ replaces net emissions $e^B(t)$ and $e^h(t,z)$, respectively. Performing the maximisation of the social welfare we obtain directly the emission standard in the benchmark case and the best-response functions (depending on z^h) in cases C and J:

$$\bar{e}^{B*} = \begin{cases} \frac{8\lambda(1+\lambda)}{D^B} & \text{if } \lambda \leq 4 \\ \frac{\lambda(6+\lambda)}{D^{B\prime}} & \text{if } \lambda \geq 4 \end{cases} \quad \text{and} \quad \bar{e}^{C,J}(z^h) = \begin{cases} \bar{e}^{B*} - \frac{\lambda(16+\lambda(16+\lambda))}{D^B} z^h & \text{if } \lambda \leq 4 \\ \bar{e}^{B*} - \frac{2\lambda(8+\lambda)}{D^{B\prime}} z^h & \text{if } \lambda \geq 4 \end{cases} \tag{24}$$

For the R&D competition and the Joint-lab cases ($h = C, J$) we obtain 'green' R&D, conditional on the standard.

$$z^C(\bar{e}^C) = \begin{cases} \frac{8\lambda^2 - \bar{e}^C\lambda(16+\lambda(24+\lambda))}{\gamma(4+3\lambda)^2+\lambda(16+\lambda(24+\lambda))} & \text{if } \lambda \leq 4 \\ \frac{\lambda(1-4\bar{e}^C)}{4\lambda+\gamma(4+\lambda)} & \text{if } \lambda \geq 4 \end{cases} \quad \text{and} \quad z^J(\bar{e}^J) = \begin{cases} \frac{16\lambda^2 - 2\lambda\bar{e}^J(16+\lambda(24+\lambda))}{\gamma(4+3\lambda)^2+2\lambda(16+\lambda(24+\lambda))} & \text{if } \lambda \leq 4 \\ \frac{2\lambda(1-4\bar{e}^J)}{8\lambda+\gamma(4+\lambda)} & \text{if } \lambda \geq 4 \end{cases} \tag{25}$$

From these best-response functions ((24) and (25)), we then calculate the SPNE outcomes for $h = C, J$. All SPNE values are reported in Tables 1 and 2 in Appendix D.

We then present a result on the equivalence between the two policy instruments, in the sense that they yield the same equilibrium outcomes. This equivalence has already been noted by Moner-Colonques and Rubio (2015, 2016) and is driven by the simple observation that the social welfare functions of the regulator are the same when setting $\bar{e} = e_i(t)$. The tax chosen by the regulator provides incentives for firms to pollute exactly as if those firms where to comply with the endogenous standard.

Proposition 0. *For all $h \in \{B, C, J\}$ and for all parameter values, equilibrium emissions, green R&D investments, consumer surplus and social welfare are identical whenever the regulator implements the equilibrium tax or standard.*

Proof. All equilibrium outcomes are provided in Tables 1 and 2 in Appendix D. □

3.4 Ranking analysis - Environmental and competition policies

In a context where firms operate under endogenous environmental regulation, we first explore whether 'green' innovation benefits the whole society. If so, second, we assess whether 'green' antitrust enhances social welfare. To that end, we use the equilibrium measures of environmental performance[11] (e), innovation (z), consumer surplus (CS), firms' profitability (π) and social welfare (SW) and provide a scenario-based comparison.

Before presenting these comparisons through the lens of R&D organization, we examine firms' ability to abate pollution.

Lemma 2. *For $\gamma, \lambda > 0$ and $d > 1$, the following ranking for abatement holds:*

$$a^{B*} > a^{C*} > a^{J*} > 0$$

where $a^{h*} = q^{h*} - z^{h*} - e^{h*}$, whatever the environmental policy instrument.

Proof. See Appendix B.

Lemma 2 states that 'green' R&D reduces the effort of standard abatement by firms, thereby helping them to better cope with costly environmental policies, whether these take the form of a tax or a standard. The induced reduction in abatement costs is even more significant when firms are able to share the costs of 'green' R&D. However, the level of abatement remains strictly positive. Indeed, the marginal benefit of 'green' R&D is a humped-shaped function of z: increasing 'green' R&D reduces abatement costs and simultaneously increases (see equations (10) and (11)). As it becomes more costly to satisfy the higher demand, through the induced-rise in pollution, firms have less incentive to further increase 'green' R&D investments. Even if 'green' R&D were costless ($\gamma = 0$), this mechanism would prevail, meaning that the required abatement effort still remains positive when $\lambda < 4$, but, when $\lambda \geq 4$, abatement drops down to 0.[12] The direct effect of 'green' R&D that reduces the abatement effort is exactly offset by the indirect effect of 'green' R&D on output/emissions, which increases the abatement effort. Of course, once R&D becomes costly, firms always adopt an R&D activity that, in equilibrium, partially reduces the total volume of abatement relative to the level of abatement without R&D (benchmark case, see equation (B.5) in the Appendix). Firms trade off the positive effect of 'green' R&D, which allows them to directly reduce the level of pollution to be abated, against its indirect effect, which results in an increase in pollution (inherent to production).

[11] Environmental performance is measured by the level of remaining emissions under an emission tax regime, while under an emissions standard it corresponds to the level of the environmental standard.

[12] Notice that when $\gamma = 0$, abatement levels are identical for $h = C, J$.

We then present the main result of the analysis, pertaining to comparisons of the relevant equilibrium values across the three scenarios considered. This is done in the following Proposition and associated Corollary.

Proposition 1. *For any $\lambda, \gamma > 0$ and $d > 1$, the following rankings hold for both environmental instruments (tax or standard):*

1. ***Ranking of emissions**: $e^{J^*} < e^{C^*} < e^{B^*}$,*
2. ***Ranking of green R&D**: $z^{J^*} > z^{C^*} > 0$,*
3. ***Ranking of Consumer Surplus**: $CS^{J^*} > CS^{C^*} > CS^{B^*}$,*
4. ***Ranking of firm profitability**: $\pi^{J^*} > \pi^{C^*} > \pi^{B^*}$,*
5. ***Ranking of Social Welfare**: $SW^{J^*} > SW^{C^*} > SW^{B^*}$.*

Proof. See Appendix C. □

We now offer the following comments: (i) Green innovation efforts undertaken by firms contribute to a more ambitious environmental policy by reducing equilibrium pollution levels, irrespective of whether firms compete or cooperate in R&D(ii) In addition, the shared-costs of R&D in the joint lab offer extra incentives for firms to invest more, compared with the competitive setting, for any e (or $\bar{e}$) (iii) As far as equilibrium output is considered, two opposite effects arise: On the one hand, the binding environmental policy (either indirectly through taxation or directly through an emission standard) reduces equilibrium output (see equations (10) and (11)) as expected. On the other hand, the output also directly increases with individual 'green' R&D effort. Overall, this last positive effect dominates and since 'green' R&D efforts are larger in the case of the joint lab, so does output as well as consumer surplus. Moreover and different from the standard Bertrand competition, because abatement costs are convex, the price quoted by firms lies above the marginal cost, which enables them to achieve larger profits. In addition, costly 'green' R&D efforts, by cutting abatement costs, lead to increased profits, more so in the joint lab since R&D costs are equally shared. (iv) Finally, as consumer and producer surplus are higher and the damage is lower, social welfare in the joint lab scenario is larger.

Against the conventional view that consumers bear environmental policy costs (higher prices etc.), in this Proposition we claim that *cooperative 'green' R&D investments benefit* ***both*** *consumers and the environment.* This conclusion provides support to the current European stance on 'green' antitrust and, at the very least, calls for a reassessment of

competition policy in light of climate goals and climate change initiatives (Inderst and Thomas, 2023). We can even go a step further as stated in the following Corollary:

Corollary 1. *For $\lambda \geq 4$ and $d > 1$, the joint lab outperforms competition in 'green' R&D in terms of 'green' innovation, reduction of pollution, consumer and producer surplus, while firms adopt tacit collusion in their price setting.*

Proof. See Lemma 1 and the proof of Proposition 1. □

Because the convexity of abatement costs is sufficiently high ($\lambda \geq 4$), firms tacitly coordinate on the collusive price equilibrium in the pricing stage of the game, as per Lemma 1. Considering this last-stage price equilibrium, when firms collaborate in the form of a joint lab in the first stage and maximize the sum of their individual profits, the resulting equilibrium for the entire game is effectively fully collusive. We thus obtain an intriguing and rather strong result whereby despite the collusive nature of this equilibrium outcome, Proposition 1 demonstrates that the joint lab configuration is a *win-win-win* solution[13] compared both to competition in green R&D and to the benchmark scenario where firms do not to invest in R&D.

4 Extension: Cournot competition

The robustness of the results presented in Section 3 is now assessed for the case of Cournot competition. In the Cournot setting, during the last stage of the game, firms choose their output by maximizing profit with respect to quantity. More precisely, when an environmental tax is applied, firms maximize equation (5) w.r.t. q_i, and when an environmental standard is implemented, they maximize (23) w.r.t. q_i. We thus obtain the following best-response functions:

$$\tilde{q}_i^h(q_j, e_i, z_i) = \frac{1 - q_j + (e_i + z_i)\lambda}{2 + \lambda} \quad \text{for } i \neq j \text{ and } i, j = 1, 2. \tag{26}$$

In the benchmark case, $h = B$, $z_i = z_j = 0$ and for any $h = B, C, J$ when an environmental standard is implemented, $e_i = \bar{e}$. Solving the output stage, we obtain equilibrium

[13] See also Agliardi and Lambertini (2024) for a win-win solution on a different context.

outputs:

$$\begin{aligned} q_i^h(e_i, e_j, z_i, z_j) &= \frac{1+\lambda(1-e_j-z_j+(e_i+z_i)(2+\lambda))}{(3+\lambda)(1+\lambda)} \\ &= q^B(e_i, e_j) + \frac{\lambda(z_i(2+\lambda)-z_j)}{(1+\lambda)(3+\lambda)} \end{aligned} \tag{27}$$

where $q^B(e_i, e_j) = \frac{1+\lambda(1-e_j+e_i(2+\lambda))}{(3+\lambda)(1+\lambda)}$ is the equilibrium output in the Benchmark case.Expression (27) holds when an environmental standard is implemented, simply replacing $e_i = e_j = \bar{e}$ for all $h = B, C, J$. In addition, when $h = J$, firms form a joint lab, they share a common effort of green R&D, so that $z_i = z_j = z^J$.

Subsequently, we derive the reduced-form of the profit functions and solve for the SPNE following the same steps as in the Bertrand competition setting (see Section 3). All details are provided in Appendices E and G.

4.1 Environmental tax

When a tax is applied, at the second stage of the game, firms choose their emissions. However, different from the Bertrand setting, the maximization of the profit function with respect to e_i involves a strategic choice by firm i, meaning that its decision depends on the rival's decision e_j.

Consequently, firms can choose their emissions either individually or cooperatively. Intuitively, we expect firms to have private incentives to agree on emissions in order to increase profits. Recent real-life examples have indeed brought up attention on such possible illicit agreements and the potential harmful effects of such anti-competitive behaviour when emissions are concerned. For instance, European truck manufacturers agreed on delaying the introduction of a new engine technology that would have lowered emissions. In 2017, the European Commission revealed that emissions indeed increased and sanctioned them. An other example deals with several German automakers who colluded to restrict competition in emission cleaning technology for their diesel cars (Inderst et al., 2023). They jointly reduced the amount of Adblue injected in the exhaust stream to clean nitrogen oxides (NOx), making their cars more polluting than they would have been without the illegal cartel agreement.

Therefore, it is necessary to assess the impact of such strategic behaviour on economic and environmental outcomes. We examine in detail both cases in Appendix E while presenting the following result on the choice of firms:

Lemma 3. *If firms choose to agree on emission levels, the performance of the environmental tax is reduced with respect to the 'no agreement' strategy, for $h = C, J$, notwithstanding firms obtain higher profits.*

Proof. See Appendix E. □

Lemma 3 establishes the dominance of the 'no agreement' on emissions strategy from a well-being perspective. Indeed, although firms would prefer to coordinate on emissions since it increases profits, such a strategy weakens incentives to innovate and produce, while increasing polluting emissions, thereby reducing social welfare – regardless of firms' behaviour at the R&D stage. Furthermore, the 'green' antitrust initiatives focus on 'green' R&D cooperation which does not include agreements on emissions. Therefore, we abstract from further comparisons incorporating possible agreements on emissions. In the next Proposition, we confirm that the comparisons of equilibrium values in the Bertrand case (see Proposition 1 above) carry over to the case of Cournot competition, provided that firms do not collude on emissions.

Proposition 2. *Proposition 1 holds if and only if firms do not agree on emission levels.*

Proof. See Appendix F. □

Proposition 2 reinforces the results established in the previous section on Bertrand competition. Indeed, we show that whenever an emission tax is implemented, no matter whether firms compete in price or quantity, allowing them to cooperate in 'green' R&D is beneficial to consumers, producers, society as a whole as well as the environment. But, it also points out that that the benefits of 'green' antitrust arise if and only if firms do not engage in anti-competitive behaviour as far as pollution-emission decisions are concerned.

4.2 Environmental standard

When a standard is implemented, the second (emission choice) stage of the game vanishes. Therefore, the issue of emissions coordination is mute. Nevertheless, the strategic behaviour in 'green' R&D along with the standard implementation still remains. Here too we perform a similar analysis as in the Bertrand setting and provide full details in G. We find that the comparison with the analogous situation under Bertrand competition is more nuanced, and depends on parameter values, namely the extent of damage d and the effectiveness of 'green' R&D. The following proposition summarises:

Proposition 3. *For any $\lambda > 0$, Proposition 1 holds only for $\gamma > 2$, and $d \geq \max\{\bar{d}, d_0\}$, where $\bar{d} = \frac{\gamma(4+3\lambda)}{2(2+\lambda)(\gamma-2)}$ and d_0 is the solution of $\bar{\pi}^{C*}(d_0) = \bar{\pi}^{B*}(d_0)$.*

Proof. See Appendix G. □

Proposition 3 is consistent with our previous results although conditions to obtain a 'win-win-win' outcome are slightly more restrictive. In particular, in a Cournot competition setting and when the regulator implements a standard, the joint lab is again the most profitable option for firms. We use Figure 2 to illustrate: The range of parameter values for which Proposition 1 holds corresponds to area A in Figure 2 ($d \geq \bar{d}$). In addition, in area D, the joint lab still generates the highest surplus for both consumers and producers as well as the lowest polluting emissions although a competitive setting becomes relatively less profitable with respect to the benchmark configuration ($d > d_0$). On the contrary, when the environmental damage is limited, $d < \bar{d}$ or/and R&D is cost-efficient, $\gamma \leq 2$, competition in 'green' R&D can lead to better environmental performance as well as larger consumer surplus. Indeed, under these parametric configurations, competition provides stronger incentives to invest in 'green' R&D, which further stimulates production and increases consumer surplus but also involves a stricter environmental standard. This corresponds to areas B and C in Figure 2.

Therefore, in a Cournot competition setting, the relaxation of competition policy to support 'green' antitrust requires a larger marginal environmental damage and/or poor R&D effectiveness. Furthermore, while 'green' antitrust may bring forward benefits for society as a whole, this also leads to crowding-out the less desirable configuration for both consumers and the environment, when the environmental damage is small. We can then claim the following:

Corollary 2. *Authorizing cooperation in 'green' R&D in the form of joint lab is generally beneficial and avoids the least desirable configuration for consumers and the environment.*

When firms are allowed to cooperate, they choose to do so as they earn higher profits. Of course, when the damage is high, this also entails overall larger social welfare (Area A in Figure 2). When the damage is low or R&D is relatively easy, it may lead to some inefficiencies, as the environmental performance and the consumer surplus are reduced in comparison with a scenario where firms compete in 'green' R&D. However, despite these worse outcomes, forming a joint lab remains more desirable than not investing in

[14] The figure is robust to alternative positive values of λ.

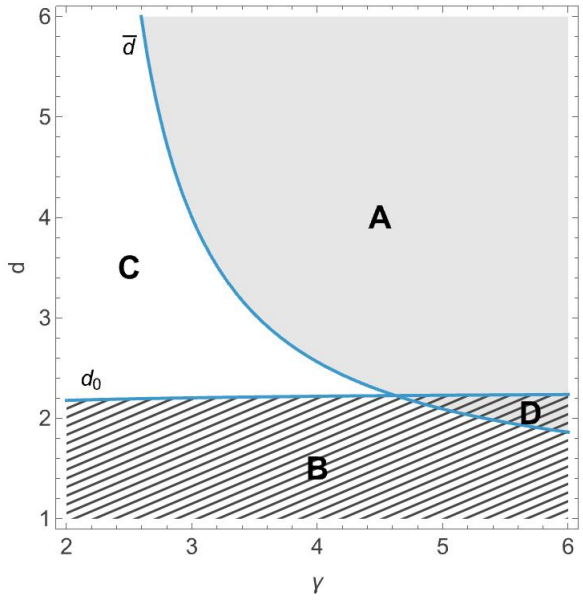


Figure 2: Benchmark, Competition and Joint Lab equilibrium outcomes ($\lambda = 5$).[14]

Area A: $\bar{e}_c{}^{J*} < \bar{e}_c{}^{C*} < \bar{e}_c{}^{B*}$, $\bar{z}_c{}^{J*} > \bar{z}_c{}^{C*}$, $\bar{CS}_c{}^{J*} > \bar{CS}_c{}^{C*} > \bar{CS}_c{}^{B*}$ and $\bar{\pi}_c{}^{J*} > \bar{\pi}_c{}^{C*} > \bar{\pi}_c{}^{B*}$
Area B: $\bar{e}_c{}^{C*} < \bar{e}_c{}^{J*} < \bar{e}_c{}^{B*}$, $\bar{z}_c{}^{C*} > \bar{z}_c{}^{J*}$, $\bar{CS}_c{}^{C*} > \bar{CS}_c{}^{J*} > \bar{CS}_c{}^{B*}$ and $\bar{\pi}_c{}^{J*} > \bar{\pi}_c{}^{B*} > \bar{\pi}_c{}^{C*}$
Area C: $\bar{e}_c{}^{C*} < \bar{e}_c{}^{J*} < \bar{e}_c{}^{B*}$, $\bar{z}_c{}^{C*} > \bar{z}_c{}^{J*}$, $\bar{CS}_c{}^{C*} > \bar{CS}_c{}^{J*} > \bar{CS}_c{}^{B*}$ and $\bar{\pi}_c{}^{J*} > \bar{\pi}_c{}^{C*} > \bar{\pi}_c{}^{B*}$
Area D: $\bar{e}_c{}^{J*} < \bar{e}_c{}^{C*} < \bar{e}_c{}^{B*}$, $\bar{z}_c{}^{J*} > \bar{z}_c{}^{C*}$, $\bar{CS}_c{}^{J*} > \bar{CS}_c{}^{C*} > \bar{CS}_c{}^{B*}$ and $\bar{\pi}_c{}^{J*} > \bar{\pi}_c{}^{B*} > \bar{\pi}_c{}^{C*}$

'green' R&D at all, which would happen if cooperation were not allowed (Areas B and D in Figure 2).

5 Concluding Remarks

In this paper we have explored the use of environmental regulation in the form of either an emissions tax or an emissions standard in a setting where firms can engage in 'green' R&D to improve emissions while they compete in the product market either in prices or in quantities. Furthermore, we have allowed for different organisational setups with respect to the conduct of R&D, i.e., either competitive or collaborative R&D, the latter in the form of a joint lab. In general, the joint lab appears to be a better organisational form, especially in the case of Bertrand (price) competition, resulting in a better outcome both for the environmental magnitudes but also for consumers and general welfare. This rather strong result carries over to the case of Cournot (quantity) competition, but depends on the relative magnitude of environmental damage and effectiveness of 'green' R&D. Hence, the main policy implication of our analysis supports 'green antitrust': allowing firms to collaborate in 'green' R&D results in higher welfare, less pollution and

improved consumer surplus.

The results we obtain provide clear guidance on the current policy debate surrounding 'green' antitrust. We show that 'green' antitrust can unambiguously improve the effectiveness of environmental policy. This result is robust to alternative market structures and modes of competition, as well as to different types of environmental policy instrument. Importantly, joint lab arrangements do not require a full verification of sustainability benefits in order to be assessed. Instead, simple information on the level of abatement activity is sufficient to evaluate whether the agreement is welfare-improving. In this sense, the evidence suggests that 'green' antitrust can meaningfully contribute to the fight against climate change. Overall, the answer to the question of whether 'green' antitrust contributes in addressing climate change is affirmative.

Appendix

A Proof of Lemma 1

$\bar{p}$ is the solution to equation (3), such that for any $p > \bar{p}$, $\hat{\pi}_i(p,1) > \hat{\pi}_i(p,2)$: each firm has an incentive to deviate by setting a lower price. This corresponds to the standard 'price war'. For given $e^h > 0$ and $z^h \geq 0$, define the minimum lower bound $p_{\min} \in (0, p_{\max})$ as the lowest price that sustains production in the second stage: $\hat{\pi}_i(p,2) = 0$ or $\hat{\pi}_i(p,2) = c_i(z_i)$ when $z_i > 0$. This minimum price is therefore

$$p^h_{min} = p^{col\,h} - \frac{2}{4+\lambda}\sqrt{1 + 2\lambda(e^h + z^h)(1 - 2(e^h + z^h))} \quad \text{for} \quad z^h \geq 0$$

The requirement that the abatement level be non-negative for all prices, $a_i(p) \geq 0$, implies $(e+z) \leq 1/2$ for $z^h \geq 0$. It follows directly from the preceding expression that $p^h_{min} < p^{col\,h}$. Next consider the difference between $\bar{p}^h$ and p^h_{min}, whose sign is given by $(8 + 16(e+z)\lambda - (e+z)^2(16 + \lambda(24+\lambda)))$. For $(e+z) \leq 1/2$, this expression is strictly positive. Then for all $p \in (p_{min}, \bar{p})$, $\hat{\pi}_i(p,2) \geq \hat{\pi}_i(p,1)$. Therefore, any firm has an incentive to deviate by setting a lower price. As a consequence, any price p belonging to this interval can be sustained as an equilibrium price (see Dastidar (1995)).

Using (6), (8), (10), (11), we complete the ranking of different prices for $\lambda > 0$:

$$\begin{cases} p^h_{min} < \bar{p}^h < p^{col\,h} & \text{if } \lambda < 4 \\ p^h_{min} < \bar{p}^h = p^{col\,h} & \text{if } \lambda = 4 \\ p^h_{min} < p^{col\,h} < \bar{p}^h & \text{if } \lambda > 4 \end{cases}$$

for all $h = B, C, J$. For $\lambda < 4$, $p^{col} \notin (p_{min}, \bar{p})$. Then, the highest possible level of $\hat{\pi}_i(p,2)$ is reached for $p = \bar{p}$ when both firms quote the same price. Therefore, $\bar{p}$ is the selected equilibrium price. When $\lambda = 4$, $\bar{p} = p^{col}$, meaning that $\hat{\pi}_i(\bar{p},2) = \hat{\pi}_i(\bar{p},1) = \hat{\pi}_i(p^{col},2)$ which is the maximum value of $\hat{\pi}(p,2)$. Then, $\bar{p} = p^{col}$ is the selected equilibrium price. When $\lambda > 4$, $p^{col} \in (p_{min}, \bar{p})$ and since $\hat{\pi}_i(p,2) \geq \hat{\pi}_i(p,1)$ and $p^{col} = argmax\{\hat{\pi}_i(p,2)\}$, then p^{col} is the selected equilibrium price. □

B Proof of Lemma 2

First, from Tables 1 and 2, and since $z^{B^*} = 0$, we compute $a^{B^*} = q^{B^*} - e^{B^*}$:

$$a^{B^*} = \begin{cases} \frac{-2\lambda^2+4d(4+3\lambda)}{D^B} & \text{if } \lambda \leq 4, \\ \frac{-\lambda+d(4+\lambda)}{D^{B\prime}} & \text{if } \lambda \geq 4. \end{cases} \tag{B.1}$$

Thus, abatement is always positive for $d > 1$.
Second, for $h = C, J$, we can express a^{h^*} depending on z^{h^*}. Inserting equation (7) into equation (10) when $\lambda \leq 4$ and equation (9) into equation (11) when $\lambda \geq 4$, we obtain:

$$q^h(z^h) = \begin{cases} \frac{2}{4+3\lambda} + \frac{2\lambda}{4+3\lambda} e^h(t^h(z^h), z^h) + \frac{2\lambda}{4+3\lambda} z^h & \text{if } \lambda \leq 4, \\ \frac{1}{4+\lambda} + \frac{\lambda}{4+\lambda} e^h(t^h(z^h), z^h) + \frac{\lambda}{4+\lambda} z^h & \text{if } \lambda \geq 4. \end{cases} \tag{B.2}$$

Next, inserting (22) into equation (14), we obtain:

$$e^h(z^h) = \begin{cases} e^{B^*} - \frac{\lambda(16+\lambda(16+\lambda))}{D^B} z^h & \text{if } \lambda \leq 4 \\ e^{B^*} - \frac{2\lambda(8+\lambda)}{D^{B\prime}} z^h & \text{if } \lambda \geq 4. \end{cases} \tag{B.3}$$

The equation above holds for $e^{B^*} = \bar{e}^{B^*}$ and corresponds to equation (24) in the equilibrium analysis when a standard is implemented. Then, our demonstration holds in both cases. Putting equation (B.3) into (B.2), we obtain, for $h = C, J$:

$$q^h(z^h) = \begin{cases} \bar{q}^{B^*} + \frac{4\lambda d(4+3\lambda)}{D^B} z^h & \text{if } \lambda \leq 4, \\ q^{col\,B^*} + \frac{2\lambda d(4+\lambda)}{D^{B\prime}} z^h & \text{if } \lambda \geq 4. \end{cases} \tag{B.4}$$

Then, by definition of a^{h^*} and using (B.1)-(B.4), we deduce that, for $h = C, J$:

$$a^h(z^h) = \begin{cases} a^{B^*} - \frac{2d(4+3\lambda)(4+\lambda)}{D^B} z^h & \text{if } \lambda \leq 4, \\ a^{B^*} - \frac{8d(4+\lambda)}{D^{B\prime}} z^h & \text{if } \lambda \geq 4. \end{cases} \tag{B.5}$$

which is strictly positive when z^h is low enough. Otherwise, $a^h(z^h) = 0$. Finally, using

the SPNE outcomes from Tables 1 and 2, we can show that:

$$z^{h^*} < \begin{cases} \frac{2d(4+3\lambda)-\lambda^2}{d(4+3\lambda)(4+\lambda)} & \text{if } \lambda \leq 4 \\ \frac{d(4+\lambda)-\lambda}{4d(4+\lambda)} & \text{if } \lambda \geq 4 \end{cases} \quad \text{for } \gamma > 0,\ d > 1, \text{ so that } a^{h^*} > 0\,, \text{for } h = C, J. \tag{B.6}$$

We have established that firms always bear a strictly positive abatement cost. In addition, from Table 1, for $\lambda \leq 4$, we have that $z^{J^*} > z^{C^*} \Rightarrow 2D^C > D^J \Rightarrow 2d\gamma(4+3\lambda)^2 + \lambda\gamma(16+\lambda(16+\lambda)) > 0$, which is always true. From Table 2, for $\lambda \geq 4$, we have that $z^{J^*} > z^{C^*} \Rightarrow 2D^{C'} > D^{J'} \Rightarrow 2d(4+\lambda)(\gamma(4+\lambda)+4\lambda) + 2\lambda\gamma(8+\lambda) > 0$, which is always true. To conclude, we can rank equilibrium abatement levels as follows: $a^{B^*} > a^{C^*} > a^{J^*} > 0$. □

C Proof of Proposition 1

We proceed in parts:

(i) From the proof of Lemma 2, $z^{J^*} > z^{C^*} > 0$ for all $\lambda > 0$. Then, from equation (B.3), it is easy to see that $e^{J^*} < e^{C^*} < e^{B^*}$.

(ii) From equation (B.4), $q^{C^*} > q^{B^*}$ and $q^{J^*} > q^{B^*}$ for $z^{h^*} > 0$, which is always true. Moreover, $q^{J^*} > q^{C^*}$ iff $z^{J^*} > z^{C^*}$, which is always true. This implies that $CS^{J^*} > CS^{C^*} > CS^{B^*}$.

(iii) From the equilibrium outcomes in Tables 1 and 2 and the reduced-form profit functions (see equation (12)), we calculate profit differences:

$$\pi^{C^*} - \pi^{B^*} = \begin{cases} \dfrac{32A\lambda^4\left(-\gamma\lambda^2 B + 4d^2C(\gamma C + D)\right)}{(D^C \cdot D^B)^2} & \text{if } \lambda \leq 4, \\ \dfrac{\lambda^2(\lambda - d(4+\lambda))^2\left(-\gamma\lambda^2 E + d^2 FG\right)}{(D^{C'} \cdot D^{B'})^2} & \text{if } \lambda \geq 4. \end{cases}$$

$$\pi^{J^*} - \pi^{C^*} = \begin{cases} \dfrac{32A\gamma\lambda^4\left(-\gamma^2\lambda^2 B + 4d^2(\gamma C + D)(\gamma C + 2D)\right)}{(D^C \cdot D^J)^2} & \text{if } \lambda \leq 4, \\ \dfrac{\gamma\lambda^2(\lambda - d(4+\lambda))^2\left(-\gamma^2\lambda^2 E + d^2 FGH\right)}{(D^{C'} \cdot D^{J'})^2} & \text{if } \lambda \geq 4. \end{cases}$$

where $A = (2d-1)^2$, $B = (16+\lambda(16+\lambda))^2$, $C = (4+3\lambda)^2$, $D = \lambda(16+\lambda(24+\lambda))$, $E = (8+\lambda)^2$, $F = (4+\lambda)^2$, $G = (4\lambda + \gamma(4+\lambda))$, $H = (8\lambda + \gamma(4+\lambda))$. For

$d > 1$, we can deduce that theses differences are always positive. We conclude that $\pi^{J^*} > \pi^{C^*} > \pi^{B^*}$.

(iv) Since $CS^{J^*} > CS^{C^*} > CS^{B^*}$, $\pi^{J^*} > \pi^{C^*} > \pi^{B^*}$ and $e^{J^*} < e^{C^*} < e^{B^*}$, we can deduce that $SW^{J^*} > SW^{C^*} > SW^{B^*}$.

□

D SPNE outcomes in Bertrand competition

Table 1: SPNE outcomes in Bertrand competition with an environmental tax/environmental standard for $\lambda \leq 4$

h	B	C	J
$e^{h*} = \bar{e}^{h*}$	$\frac{8\lambda(1+\lambda)}{D^B}$	$\frac{8\lambda(\gamma+\lambda+\gamma\lambda)}{D^C}$	$\frac{8\lambda(\gamma+2\lambda+\gamma\lambda)}{D^J}$
$z^{h*} = \bar{z}^{h*}$	0	$\frac{8\lambda^2(2d-1)}{D^C}$	$\frac{16\lambda^2(2d-1)}{D^J}$
$q^{h*} = \bar{q}^{h*}$	$\frac{2(2d+\lambda)(4+3\lambda)}{D^B}$	$\frac{2(4+3\lambda)(\gamma\lambda+2d(\gamma+\lambda))}{D^C}$	$\frac{2(4+3\lambda)(\gamma\lambda+2d(\gamma+2\lambda))}{D^J}$
$\bar{\pi}^{h*} = \pi^{h*} - t^{h*}e^{h*}$	$\lambda(q^{B*})^2 - \frac{\lambda}{2}(e^{B*})^2$	$\lambda(q^{C*})^2 - \frac{\lambda}{2}(e^{C*}+z^{C*})^2 - \frac{\gamma}{2}(z^{C*})^2$	$\lambda(q^{J*})^2 - \frac{\lambda}{2}(e^{J*}+z^{J*})^2 - \frac{\gamma}{4}(z^{J*})^2$
$SW^{h*} = S\bar{W}^{h*}$	$\frac{8(2d+\lambda)(1+\lambda)}{D^B}$	$2\left((q^{C*})^2 + \bar{\pi}^{C*} - d(e^{C*})^2\right)$	$2\left((q^{J*})^2 + \bar{\pi}^{J*} - d(e^{J*})^2\right)$

$D^B = 2d(4+3\lambda)^2 + \lambda(16+\lambda(16+\lambda))$, $D^C = 2d(\gamma(4+3\lambda)^2 + \lambda(16+\lambda(24+\lambda))) + \lambda\gamma(16+\lambda(16+\lambda))$,
$D^J = 2d(\gamma(4+3\lambda)^2 + 2\lambda(16+\lambda(24+\lambda))) + \lambda\gamma(16+\lambda(16+\lambda))$.

Table 2: SPNE outcomes in Bertrand competition with an environmental tax/environmental standard for $\lambda \geq 4$

h	B	C	J
$e^{h*} = \bar{e}^{h*}$	$\frac{\lambda(6+\lambda)}{D^{B'}}$	$\frac{\lambda(2\lambda+\gamma(6+\lambda))}{D^{C'}}$	$\frac{\lambda(4\lambda+\gamma(6+\lambda))}{D^{J'}}$
$z^{h*} = \bar{z}^{h*}$	0	$\frac{2\lambda(d(4+\lambda)-\lambda)}{D^{C'}}$	$\frac{4\lambda(d(4+\lambda)-\lambda)}{D^{J'}}$
q^{h*}	$\frac{(2d+\lambda)(4+\lambda)}{D^{B'}}$	$\frac{(4+\lambda)(\gamma\lambda+2d(\gamma+\lambda))}{D^{C'}}$	$\frac{(4+\lambda)(\gamma\lambda+2d(\gamma+2\lambda))}{D^{J'}}$
$\bar{\pi}^{h*} = \pi^{h*} - t^{h*}e^{h*}$	$(2+\lambda)(q^{B*})^2 - \frac{\lambda}{2}(e^{B*})^2$	$(2+\lambda)(q^{C*})^2 - \frac{\lambda}{2}(e^{C*}+z^{C*})^2 - \frac{\gamma}{2}(z^{C*})^2$	$(2+\lambda)(q^{J*})^2 - \frac{\lambda}{2}(e^{J*}+z^{J*})^2 - \frac{\gamma}{4}(z^{J*})^2$
$SW^{h*} = S\bar{W}^{h*}$	$\frac{(2d+\lambda)(6+\lambda)}{D^{B'}}$	$2\left((q^{C*})^2 + \bar{\pi}^{C*} - d(e^{C*})^2\right)$	$2\left((q^{J*})^2 + \bar{\pi}^{J*} - d(e^{J*})^2\right)$

$D^{B'} = 2d(4+\lambda)^2 + 2\lambda(8+\lambda)$, $D^{C'} = 2d(4+\lambda)(4\lambda+\gamma(4+\lambda)) + 2\lambda\gamma(8+\lambda)$, $D^{J'} = 2d(4+\lambda)(8\lambda+\gamma(4+\lambda)) + 2\lambda\gamma(8+\lambda)$.

E Proof of Lemma 3

In this Appendix, we derive the equilibrium outcomes in the Cournot setting when an environmental tax is applied. We present the most general explicit form of the results. Then, to derive the Benchmark and the Joint Lab outcomes, one has to replace $z_i = z_j = 0$ or $z_i = z_j = z^J$, respectively. We distinguish two cases, whether firms coordinate or not on their emissions level. The former case will be denoted with superscript $\breve{x}$.

Equilibrium results

Using (5), (27) and the inverse linear demand, we obtain the reduced-form profit function for firm i (indexed by c for Cournot competition):

$$\pi_{i,c}^h = (1+\frac{\lambda}{2})(q_i^h(e_i,e_j,z_i,z_j))^2 - \frac{\lambda}{2}(e_i+z_i)^2 - \frac{\gamma}{2}z_i^2 - te_i. \tag{E.7}$$

At the second stage of the game, firms choose their optimal emissions level. Two possible cases may arise: *(a)* either firms maximize their individual profit ($\pi_{i,c}^h$) or *(b)* they cooperate and maximize the sum ($\sum_i \pi_{i,c}^h$). In each scenario h, with respect to e_i yields the optimal emissions level:

$$e_i^h(t,z_i^h) = e_c^B(t) - z_i^h = \begin{cases} \frac{\lambda(2+\lambda)^2 - t(1+\lambda)(3+\lambda)^2}{\lambda(9+\lambda(11+3\lambda))} - z_i^h & \text{when } e_i^h(t,z_i^h) = argmax\, \pi_{i,c}^h \\ \frac{\lambda(2+\lambda) - t(3+\lambda)^2}{\lambda(9+4\lambda)} - z_i^h & \text{when } \breve{e}_i^h(t,z_i^h) = argmax \sum \pi_{i,c}^h. \end{cases} \tag{E.8}$$

At the first stage of the game, firms choose how much to invest in 'green' R&D (cases C and J), and the regulator decides on the optimal level of the tax. The profit maximization, for $h = C, J$, with respect to z, once the optimal level of emissions is taken into account (see equation (E.8)), yields similar results as equations (19) and (20), irrespective of the behaviour of firms (coordination or not on emissions levels). Recall that:

$$z^h(t^h) = \begin{cases} \frac{t^h}{\gamma} & \text{for } h = C \\ \frac{2t^h}{\gamma} & \text{for } h = J \end{cases}$$

Simultaneously, the regulator maximizes social welfare deciding upon t.

$$t^h(z^h) = \begin{cases} {t_c}^{B^*} - \frac{2d\lambda(9+\lambda(11+3\lambda))}{D_c^B} z^h & \text{when } e_i^h(t,z_i^h) = argmax\, \pi_{i,c}^h \\ \breve{t}_c{}^{B^*} - \frac{2d\lambda(9+4\lambda)}{D_c^{B'}} z^h & \text{when } \breve{e}_i^h(t,z_i^h) = argmax \sum \pi_{i,c}^h \end{cases} \tag{E.9}$$

with ${t_c}^{B^*} = \frac{\lambda(2d(2+\lambda)^2 - \lambda^2)}{(1+\lambda)D_c^B}$, $\breve{t}_c{}^{B^*} = \frac{2\lambda(d(2+\lambda)-\lambda)}{D_c^B}$ and $D_c^B = 2d(3+\lambda)^2 + \lambda(9+2\lambda) > 0$. From the best-response functions $z^h(t^h)$ and equation (E.10), it is then straightforward

to obtain the equilibrium tax:

$$\begin{array}{cc} \text{without agreement on } e & \text{with agreement on } e \\ t_c^{h*} = \begin{cases} \frac{\lambda\left(2d(2+\lambda)^2-\lambda^2\right)}{(1+\lambda)D_c^B} & \text{for } h=B \\ \frac{\gamma\lambda\left(2d(2+\lambda)^2-\lambda^2\right)}{D_c^C} & \text{for } h=C \\ \frac{\gamma\lambda\left(2d(2+\lambda)^2-\lambda^2\right)}{D_c^J} & \text{for } h=J \end{cases} & \breve{t}_c^{h*} = \begin{cases} \frac{2\lambda(d(2+\lambda)-\lambda)}{D_c^B} & \text{for } h=B \\ \frac{2\gamma\lambda(d(2+\lambda)-\lambda)}{D_c^{C'}} & \text{for } h=C \\ \frac{2\gamma\lambda(d(2+\lambda)-\lambda)}{D_c^{J'}} & \text{for } h=J \end{cases} \end{array} \tag{E.10}$$

with $D_c^C = \gamma\lambda(1+\lambda)(9+2\lambda) + 2d(\gamma(1+\lambda)(3+\lambda)^2 + \lambda(9+\lambda(11+3\lambda)))$ and $D_c^J = \gamma\lambda(1+\lambda)(9+2\lambda) + 2d(\gamma(1+\lambda)(3+\lambda)^2 + 2\lambda(9+\lambda(11+3\lambda)))$, $D_c^{C'} = \gamma\lambda(9+2\lambda) + 2d(\gamma(3+\lambda)^2 + \lambda(9+4\lambda))$ and $D_c^{J'} = \gamma\lambda(9+2\lambda) + 2d(\gamma(3+\lambda)^2 + 2\lambda(9+4\lambda))$.

We then obtain optimal efforts in 'green' R&D and compute the remaining equilibrium results at the SPNE. These SPNE equilibrium values are reported in Appendix H.

Comparisons

Using the SPNE values from Tables 4 and 5, we compute equilibrium differences when firms agree on emissions level or not, $\forall h \in \{B, C, J\}$:

	$h=B$	$h=C$	$h=J$
$e^{h*} - \breve{e}^{h*}$	0	$\frac{-\lambda(9+2\lambda)}{D_c^C D_c^{C'}}\Omega < 0$	$\frac{-2\lambda^2(9+2\lambda)}{D_c^J D_c^{J'}}\Omega < 0$
$z^{h*} - \breve{z}^{h*}$	0	$\frac{\lambda D_c^B}{D_c^C D_c^{C'}}\Omega > 0$	$\frac{2\lambda D_c^{B'}}{D_c^J D_c^{J'}}\Omega > 0$
$q^{h*} - \breve{q}^{h*}$	0	$\frac{2d\lambda^2(3+\lambda)}{D_c^C D_c^{C'}}\Omega > 0$	$\frac{4d\lambda^2(3+\lambda)}{D_c^J D_c^{J'}}\Omega > 0$
$\pi^{h*} - \breve{\pi}^{h*}$	<0	<0	<0
$SW^{h*} - \breve{SW}^{h*}$	0	>0	>0

Table 3: Comparisons with $\Omega = (2+\lambda)(\gamma\lambda + 2d(\gamma+\lambda))$.

This proves Lemma 3.

□

F Proof of Proposition 2

Using the SPNE values from Table 4, it is straightforward to show that (i) ${t_c}^{J*} < {t_c}^{C*} < {t_c}^{B*}$, ${z_c}^{J*} > {z_c}^{C*} > 0$, (ii) ${e_c}^{J*} < {e_c}^{C*} < {e_c}^{B*}$ and (iii) ${q_c}^{J*} > {q_c}^{C*} > {q_c}^{B*}$. Hence we obtain the following ranking of equilibrium profits: ${\pi_c}^{J*} > {\pi_c}^{C*} > {\pi_c}^{B*}$ which leads to the ranking on equilibrium social welfare: ${SW_c}^{J*} > {SW_c}^{C*} > {SW_c}^{B*}$. This proves Proposition 2. □

G Proof of Proposition 3

In this Appendix, we obtain the equilibrium outcomes in the Cournot setting when an environmental standard is implemented. First, using (27), we write the reduced-form equilibrium profits for firm i as follows:

$$\pi_{i,c}^{h} = \begin{cases} \left(1+\frac{\lambda}{2}\right)\left({q_c}^{h}(\bar{e})\right)^2 - \frac{\lambda}{2}\bar{e}^2 & \text{for } h = B \\ \left(1+\frac{\lambda}{2}\right)\left({q_c}^{h}(\bar{e}, z_i, z_j)\right)^2 - \frac{\lambda}{2}(\bar{e}+z_i)^2 - \frac{\gamma}{2}z_i^2 & \text{for } h = C \\ \left(1+\frac{\lambda}{2}\right)\left({q_c}^{h}(\bar{e}, z^J)\right)^2 - \frac{\lambda}{2}(\bar{e}+z^J)^2 - \frac{\gamma}{4}(z^J)^2 & \text{for } h = J \end{cases}$$

In the first stage of the game, the regulator sets the emission cap by maximizing the social welfare function with respect to $\bar{e}$ while firms choose their 'green' R&D efforts (in setups C and J). When $h = B$, $z_i = z_j = 0$, we find the optimal environmental standard by maximising social welfare:

$$\bar{e}^{B*} = \frac{\lambda(4+\lambda)}{D_c^B}. \tag{G.11}$$

For $h = C, J$, we obtain the best-response functions at the first stage, invoking the symmetry $z_i = z_j = z^C$:

$$z_c^h(\bar{e}) = \begin{cases} \frac{\lambda\left((2+\lambda)^2 - \bar{e}^h((3+\lambda)^2(1+\lambda) - \lambda(2+\lambda)^2)\right)}{\gamma(1+\lambda)(3+\lambda)^2 + \lambda((3+\lambda)^2(1+\lambda) - \lambda(2+\lambda)^2)} & \text{for } h = C \\ \frac{2\lambda((2+\lambda) - \bar{e}^h((3+\lambda)^2 - \lambda(2+\lambda)))}{\gamma(3+\lambda)^2 + 2\lambda((3+\lambda)^2 - \lambda(2+\lambda))} & \text{for } h = J \end{cases} \tag{G.12}$$

and

$$\bar{e}_c^h(z) = \begin{cases} {\bar{e}_c}^{B*} - \frac{\lambda(9+2\lambda)}{D_c^B} z^C & \text{for } h = C \\ {\bar{e}_c}^{B*} - \frac{\lambda(9+2\lambda)}{D_c^B} z^J & \text{for } h = J. \end{cases} \tag{G.13}$$

All equilibrium results are reported in Table 6 in Appendix H.

Then, it remains to explore the rankings reported in Proposition 1 for the case when firms compete in quantities and adopt an environmental standard. From equation (G.13), it is easy to show that ${\bar{e}_c}^{B*} > {\bar{e}_c}^{h*}$ for $h = \{C, J\}$. Next, using Table 6, we can write the difference $({\bar{e}_c}^{C*} - {\bar{e}_c}^{J*})$ as:

$${\bar{e}_c}^{C*} - {\bar{e}_c}^{J*} = \frac{\lambda^3(9+2\lambda)}{D_c^C D_c^{J'}}\Psi(d, \gamma), \tag{G.14}$$

where $\Psi(d, \gamma) = 2d(2+\lambda)(\gamma-2) - \gamma(4+3\lambda)$ and D_c^h are the denominators of $\bar{e}^{h*}$ for $h = C, J$. When $\gamma \leq 2$, $\Psi(d, \gamma) < 0$ the difference ${\bar{e}_c}^{C*} - {\bar{e}_c}^{J*}$ becomes negative whatever

the other parameters values. When $\gamma > 2$, it follows that $(\bar{e}_c{}^{C*} - \bar{e}_c{}^{J*}) \geq 0$ if $\Psi(d,\gamma) \geq 0$. Note that as $\Psi'_d(d,\gamma) > 0$, there exists a critical value $\bar{d}$ such that $\Psi(d,\gamma) \geq 0$ for $d \geq \bar{d}$ and $\Psi(d,\gamma) < 0$ otherwise. This critical value is given by $\bar{d} = \frac{\gamma(4+3\lambda)}{2(2+\lambda)(\gamma-2)} > 1$. It follows that $\bar{e}_c{}^{C*} - \bar{e}_c{}^{J*} \gtreqless 0$ for $d \gtreqless \bar{d}$. In addition, the sign of $\bar{z}_c{}^{J*} - \bar{z}_c{}^{C*}$ is identical to the sign of $\Psi(d,\gamma)$. Thus, $\bar{z}_c{}^{J*} - \bar{z}_c{}^{C*} \gtreqless 0$ when $d \gtreqless \bar{d}$ and $\gamma > 2$. The same reasoning holds for the comparison of equilibrium outputs. Therefore, when $d \gtreqless \bar{d}$ and $\gamma > 2$, $\bar{q}_c{}^{J*} \gtreqless \bar{q}_c{}^{C*}$ and thus, $\bar{CS}_c{}^{J*} \gtreqless \bar{CS}_c{}^{C*}$.

Moreover, we can rewrite the profit functions as follows:

$$\bar{\pi}_c^{h^*} = \begin{cases} \bar{\pi}_c{}^{B*} + \bar{z}_c{}^{h*}\Theta\left(\frac{(2d(2+\lambda)-2\lambda)}{D_c^B}\right) - (\bar{z}_c{}^{h*})^2\frac{\lambda}{2}\left(\Theta^2\left(1 - \frac{\lambda(2+\lambda)}{(3+\lambda)^2}\right) - 1\right) & \text{for } h = C \\ \bar{\pi}_c{}^{B*} + \bar{z}_c{}^{h*}\lambda\Theta\left(\frac{(2d(2+\lambda)-2\lambda)}{D_c^B}\right) - (\bar{z}_c{}^{h*})^2\frac{\lambda}{2}\left(\Theta^2\left(1 - \frac{\lambda(2+\lambda)}{(3+\lambda)^2}\right) - \frac{1}{2}\right) & \text{for } h = J \end{cases}$$

with $\Theta = \frac{2d(3+\lambda)^2}{D_c^B} > 0$. We can deduce that $\bar{\pi}_c{}^{C*}(z) < \bar{\pi}_c{}^{J*}(z)$ for any $0 < z < z^{\max}$. Then, $\bar{\pi}_c{}^{C*}(\bar{z}_c{}^{C*}) < \bar{\pi}_c{}^{J*}(\bar{z}_c{}^{C*})$. Moreover, from the definition of the SPNE, $argmax\{\bar{\pi}_c{}^{J*}\} = \bar{z}_c{}^{J*}$. Then, $\bar{\pi}_c{}^{J*}(\bar{z}_c{}^{J*}) \geq \bar{\pi}_c{}^{J*}(\bar{z}_c^{C*})$. Then, it follows that $\bar{\pi}_c{}^{J*}(\bar{z}_c{}^{J*}) > \bar{\pi}_c{}^{C*}(\bar{z}_c{}^{C*})$. Next, using the SPNE levels of profits, we show that:

$$\bar{\pi}_c{}^{J*} - \bar{\pi}_c{}^{B*} = \frac{4\lambda^2(\lambda - d(2+\lambda))^2(-\gamma\lambda^2(9+2\lambda)^2 + 4d^2(3+\lambda)^2(\gamma(3+\lambda)^2 + 2\lambda(9+4\lambda)))}{(D_c^B)^2(\gamma D_c^B + 4d\lambda(9+4\lambda))^2}$$

which is always positive for $d > 1$. Then, $\bar{\pi}_c{}^{J*} > \max\{\bar{\pi}_c{}^{B*}, \bar{\pi}_c{}^{C*}\}$.

We then compare $\bar{\pi}_c{}^{C*}$ and $\bar{\pi}_c{}^{B*}$. Using the SPNE levels of profits, this comparison yields ambiguous results. We show that $\bar{\pi}_c{}^{C*} - \bar{\pi}_c{}^{B*} < 0$ iff

$$f(d) = \mathcal{A}(\lambda,\gamma) - \mathcal{B}(\lambda,\gamma)d + \mathcal{C}(\lambda,\gamma)d^3 - \mathcal{D}(\lambda,\gamma)d^2 < 0, \tag{G.15}$$

where $\mathcal{A}(\lambda,\gamma) = \gamma\lambda^3(9+2\lambda)^2, \mathcal{B}(\lambda,\gamma) = 2\gamma\lambda(2+\lambda)(4+\lambda)(9+2\lambda)(9+4\lambda), \mathcal{C}(\lambda,\gamma) = 8(2+\lambda)(3+\lambda)^2(\gamma(3+\lambda)^2 + \lambda(5+2\lambda)), \mathcal{D}(\lambda,\gamma) = 4(3+\lambda)^2(\lambda(36+\lambda(35+8\lambda)) + \gamma(72 + \lambda(77+\lambda(26+3\lambda))))$.

We aim to prove the existence of values of $d > 1$ such that the above inequality holds for $\gamma, \lambda > 0$. First, we show that $f(1) < 0$ and $\lim_{d\to+\infty} f(d) \to +\infty$. Indeed, $f(1) = \mathcal{A}(\lambda,\gamma) - \mathcal{B}(\lambda,\gamma) + \mathcal{C}(\lambda,\gamma) - \mathcal{D}(\lambda,\gamma) < 0$, since $\mathcal{A}(\lambda,\gamma) - \mathcal{B}(\lambda,\gamma) < 0$ and $\mathcal{C}(\lambda,\gamma) - \mathcal{D}(\lambda,\gamma) < 0$, $\forall\lambda,\gamma > 0$. In addition, $d \to +\infty$, the term $\mathcal{C}(\lambda,\gamma)d^3$ dominates, and since $\mathcal{C}(\lambda,\gamma) > 0$, we have $f(d) \to +\infty$.

By the Intermediate Value Theorem, since $f(1) < 0$ and $f(d) \to +\infty$ as $d \to +\infty$, there exists a value $d_0 > 1$ such that $f(d_0) = 0$. Therefore, for all $1 < d < d_0$, we have

$f(d) < 0$. Figure 2 is drawn as an illustration to identify for a given value of d and some range of parameters (γ, λ) when inequality (G.15) is satisfied, and when it is not.

Finally, we obtain that when $d \gtreqless \bar{d}$ and $\gamma > 2$, $S\bar{W}_c{}^{J^*} > S\bar{W}_c{}^{C^*} > S\bar{W}_c{}^{B^*}$. This completes the proof of Proposition 3. □

H SPNE outcomes in Cournot competition

Table 4: SPNE outcomes in Cournot competition with a tax when $\breve{e}_i^h(t, z_i^h) = argmax\, \pi_{i,c}^h$

h	B	C	J
${e_c}^{h*}$	$\frac{\lambda(4+\lambda)}{{D_c}^B}$	$\frac{\lambda^3+\gamma\lambda(1+\lambda)(4+\lambda)}{{D_c}^C}$	$\frac{2\lambda^3+\gamma\lambda(1+\lambda)(4+\lambda)}{{D_c}^J}$
${z_c}^{h*}$	0	$\frac{\lambda(2d(2+\lambda)^2-\lambda^2)}{D_c^C}$	$\frac{2\lambda(2d(2+\lambda)^2-\lambda^2)}{D_c^J}$
${q_c}^{h*}$	$\frac{(2d+\lambda)(3+\lambda)}{{D_c}^B}$	$\frac{(1+\lambda)(3+\lambda)(2d(\gamma+\lambda)+\lambda\gamma)}{{D_c}^C}$	$\frac{(1+\lambda)(3+\lambda)(\gamma\lambda+2d(\gamma+2\lambda))}{{D_c}^J}$
${\pi_c}^{h*}$	$\lambda({q_c}^{B*})^2 - \frac{\lambda}{2}({e_c}^{B*})^2 - {t_c}^{B*}{e_c}^{B*}$	$(1+\frac{\lambda}{2})({q_c}^{C*})^2 - \frac{\lambda}{2}({e_c}^{C*}+{z_c}^{C*})^2 - \frac{\gamma}{2}({z_c}^{C*})^2 - {e_c}^{C*}{t_c}^{C*}$	$\lambda({q_c}^{J*})^2 - \frac{\lambda}{2}({e_c}^{J*}+z^{J*})^2 - \frac{\gamma}{4}({z_c}^{J*})^2 - {e_c}^{J*}{t_c}^{J*}$
${SW_c}^{h*}$	$2\left(({q_c}^{B*})^2 + {\pi_c}^{B*} - d({e_c}^{B*})^2\right) + {t_c}^{B*}{e_c}^{B*}$	$2\left(({q_c}^{C*})^2 + {\pi_c}^{C*} - d({e_c}^{C*})^2\right) + {t_c}^{C*}{e_c}^{C*}$	$2\left(({q_c}^{J*})^2 + {\pi_c}^{J*} - d({e_c}^{J*})^2\right) + {t_c}^{J*}{e_c}^{J*}$

$D_c^B = 2d(3+\lambda)^2 + \lambda(9+2\lambda)$, ${D_c}^C = 2d(\gamma(1+\lambda)(3+\lambda)^2 + \lambda(9+\lambda(11+3\lambda))) + \gamma\lambda(1+\lambda)(9+2\lambda)$,
$D_c^J = \gamma\lambda(1+\lambda)(9+2\lambda) + 2d(\gamma(1+\lambda)(3+\lambda)^2 + 2\lambda(9+\lambda(11+3\lambda)))$.

Table 5: SPNE outcomes in Cournot competition with a tax when $e_i^h(t, z_i^h) = argmax\, \sum \pi_{i,c}^h$

h	B	C	J
${\breve{e}_c}^{h*}$	$\frac{\lambda(4+\lambda)}{{D_c}^B}$	$\frac{\lambda(2\lambda+\gamma(4+\lambda))}{D^{C\prime}}$	$\frac{\lambda(\gamma(4+\lambda)+4\lambda)}{D_c^{J\prime}}$
${\breve{z}_c}^{h*}$	0	$\frac{2\lambda(d(2+\lambda)-\lambda)}{D_c^{C\prime}}$	$\frac{4\lambda(d(2+\lambda)-\lambda)}{D_c^{J\prime}}$
${\breve{q}_c}^{h*}$	$\frac{(2d+\lambda)(3+\lambda)}{{D_c}^B}$	$\frac{(3+\lambda)(\gamma\lambda+2d(\gamma+\lambda))}{D_c^{C\prime}}$	$\frac{(3+\lambda)(2d(\gamma+2\lambda)+\lambda\gamma)}{D_c^{J\prime}}$
${\breve{\pi}_c}^{h*}$	$\lambda({\breve{q}_c}^{B*})^2 - \frac{\lambda}{2}({e_c}^{B*})^2 - {e_c}^{B*}{\breve{t}_c}^{B*}$	$\lambda({\breve{q}_c}^{C*})^2 - \frac{\lambda}{2}({\breve{e}_c}^{C*}+{\breve{z}_c}^{C*})^2 - \frac{\gamma}{2}({\breve{z}_c}^{C*})^2 - {\breve{e}_c}^{C*}{\breve{t}_c}^{C*}$	$(1+\frac{\lambda}{2})({\breve{q}_c}^{J*})^2 - \frac{\lambda}{2}({\breve{e}_c}^{J*}+{\breve{z}_c}^{J*})^2 - \frac{\gamma}{4}({\breve{z}_c}^{J*})^2 - {\breve{e}_c}^{C*}{\breve{t}_c}^{C*}$
${S\breve{W}_c}^{h*}$	$2\left(({\breve{q}_c}^{B*})^2 + {\breve{\pi}_c}^{B*} - d({e_c}^{B*})^2\right) + {e_c}^{B*}{\breve{t}_c}^{B*}$	$2\left(({\breve{q}_c}^{C*})^2 + {\breve{\pi}_c}^{C*} - d({\breve{e}_c}^{C*})^2\right) + {\breve{e}_c}^{C*}{\breve{t}_c}^{C*}$	$2\left(({\breve{q}_c}^{J*})^2 + {\breve{\pi}_c}^{J*} - d({\breve{e}_c}^{J*})^2\right) + {\breve{e}_c}^{J*}{\breve{t}_c}^{J*}$

$D_c^{C\prime} = 2d(\gamma(3+\lambda)^2 + \lambda(9+4\lambda)) + \gamma\lambda(9+2\lambda)$, $D_c^{J\prime} = \gamma\lambda(9+2\lambda) + 2d(\gamma(3+\lambda)^2 + 2\lambda(9+4\lambda))$.

Table 6: SPNE outcomes in Cournot competition with the emission standard

h	B	C	J
${\bar{e}_c}^{h*}$	$\frac{\lambda(4+\lambda)}{{D_c}^B}$	$\frac{\lambda^3+\gamma\lambda(1+\lambda)(4+\lambda)}{{D_c}^C}$	$\frac{\lambda(\gamma(4+\lambda)+4\lambda)}{D_c^{J'}}$
${\bar{z}_c}^{h*}$	0	$\frac{\lambda(2d(2+\lambda)^2-\lambda^2)}{{D_c}^C}$	$\frac{4\lambda(d(2+\lambda)-\lambda)}{D_c^{J'}}$
${\bar{q}_c}^{h*}$	$\frac{(2d+\lambda)(3+\lambda)}{{D_c}^B}$	$\frac{(1+\lambda)(3+\lambda)(2d(\gamma+\lambda)+\lambda\gamma)}{{D_c}^C}$	$\frac{(3+\lambda)(2d(\gamma+2\lambda)+\lambda\gamma)}{D_c^{J'}}$
${\bar{\pi}_c}^{h*}$	$(1+\frac{\lambda}{2})({\bar{q}_c}^{B*})^2-\frac{\lambda}{2}({\bar{e}_c}^{B*})^2$	$(1+\frac{\lambda}{2})({\bar{q}_c}^{C*})^2-\frac{\lambda}{2}({\bar{e}_c}^{C*}+{\bar{z}_c}^{C*})^2-\frac{\gamma}{2}({\bar{z}_c}^{C*})^2$	$(1+\frac{\lambda}{2})({\bar{q}_c}^{J*})^2-\frac{\lambda}{2}({\bar{e}_c}^{J*}+{\bar{z}_c}^{J*})^2-\frac{\gamma}{4}({\bar{z}_c}^{J*})^2$
${SW_c}^{h*}$	$2\left(({\bar{q}_c}^{B*})^2+{\bar{\pi}_c}^{B*}-d({\bar{e}_c}^{B*})^2\right)$	$2\left(({\bar{q}_c}^{C*})^2+{\bar{\pi}_c}^{C*}-d({\bar{e}_c}^{C*})^2\right)$	$2\left(({\bar{q}_c}^{J*})^2+{\bar{\pi}_c}^{J*}-d({\bar{e}_c}^{J*})^2\right)$

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