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# Can Cleaner Environment Promote International Trade? Environmental Policies as Export Promoting Mechanisms

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**Abstract**
We examine whether environmental protection enhances international trade in a model of an international duopoly where production uses a depletable resource and generates cross-border pollution, and firms export their output to a world-market. Governments control pollution via either an emission tax, with revenue being used either to finance public pollution abatement or being refunded to the emitting firm contingent on reducing the cost of private pollution abatement (revenue-recycling), or an environmentally related standard. We evaluate these policies in terms of promoting exports, conserving the endowment of the natural resource, reducing pollution, and enhancing welfare. Our results indicate that in most cases, (1) revenue recycling is an export-contracting but resource preserving policy which also encourages firms' pollution abatement activity, (2) public pollution abatement is an export-promoting but resource depleting policy. When the public sector is efficient in abating pollution, then overall pollution level across countries is lower compared to their level under tax-revenue recycling. Both policies entail ambiguous welfare effects. Environmental standards relative to public abatement is an export-contracting but resource preserving policy. Relative to revenue recycling work in the opposite way; they are always, however, welfare-enhancing.

**Keywords** Emission taxation · Public pollution abatement · Recycling tax revenues · Environmentally related standards · International trade

**JEL Classification** F18 · H23 · Q58

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# 1 Introduction

## 1.1 The Issue

Traditionally and for a long time, price and quantity related trade policy instruments, such as, export subsidies, import tariffs and quotas, have been adopted in the countries pursuit of trade policy objectives, e.g., strategic use of policy instruments to bolster the position of domestic firms and sectors on foreign (world) markets, to enhance domestic production and employment, to countervail the adoption of trade policy measures by other countries, e.g., anti-dumping and countervailing duties. Nowadays, in an era where *GATT/WTO* initiatives fiercely promote the liberalization of world trade, member-countries, are restricted from using such export-promoting or import-restricting policies.[1] Given that the past rounds of *GATT/WTO* negotiations have been successful in lowering export subsidies and tariffs in most of its member-countries, the remaining issues to address, involve, by and large, issues of national interest indirectly related to trade. One of those issues is the environment.

Most countries have national laws governing environmental measures and policies, e.g., environmental taxes, standards (product and process standards, trade in hazardous elements, criminal and civil law), tradable and non-tradable emissions permits.[2] Article XX, of GATT known as the "*Green Provision*"allows countries to adopt (such) own environmental policies provided that (i) are uniformly applied and do not discriminate between domestic and foreign producers, (ii) are not applied in a manner which constitutes a disguised restriction on international trade, and (iii) protect human, animal or plant life or health, and the conservation of exhaustible natural resources. In light of the above, national environmental policies along with increased environmental awareness have provided stronger incentives to invest in "greener" technologies, and increased production and trade of environmentally friendlier products, particularly when revenues from such policies are refunded to polluting agents. Inevitably, however, environmental measures have also emerged as strategic policies which can afford promotion or disruption of international trade.

Against this evidence, the environment-international trade nexus, e.g., *Do, and if so, how environmental policies enhance international trade* ?, remains inadequately addressed. The present study aims to provide new insights to this policy dilemma. In this pursuit, we assess the effectiveness of distinct environmental policies, as measures of promoting exports, i.e., of expanding a country's share in world markets, of protecting the endowment of natural resources, and as measures of curbing pollution emissions, which can be either local or transboundary in nature. Related to these objectives we also examine their impact on national welfare.[3]

[1] For example, the Hong Kong Round of the WTO in 2005, mandated, among other measures, the gradual abolition of direct and indirect agricultural export subsidies by 2013, the immediate abolition of export subsidies on cotton and the granting of unrestricted access for cotton exports from W. Africa and other least developed countries to markets of developed economies, e.g., the EU, the US, Canada and Japan, agreement on (size) reduction of trade-distorting subsidies, and their shifting into product categories sheltered from deep cuts, e.g., so-named "national brands" or "traditional" products.

[2] In December 2015, 195 countries signed the Paris climate agreement (COP21), the first-ever universal, legally binding global climate accord. However, recent political developments unveil the difficulties regarding the implementation of this agreement.

[3] Copeland and Taylor (2004), Copeland (2011), and Copeland (2012) provide an excellent survey of such trade and environment related issues. In addition, an extensive literature examines the impact of Non-tariif Measures (NTMs), e.g., environmental regulations, technical barriers to trade (*TBT* s), Sanitary and Phy-

Without claiming that the present endeavor exhausts the range of environmental policies to a government, here, motivated by substantial real world evidence, we focus on two widely used instruments of environmental policy; (i) emission taxes, and (ii) environmentally related standards, hereon *ERS*s.[4] Furthermore, and again supported by strong real world evidence, we focus on two notable uses of emissions tax revenue. The first is the so called *revenue recycling scheme*. We assume that governments rebate environmental tax revenues partly to polluting firms as an incentive to adopt cleaner production technologies, and partly to local households. The second is the so-called provision of *public pollution abatement* activity. By this, governments finance their own pollution abatement initiatives, alongside with private sector pollution abatement programs.

Refunding or recycling of environmental tax revenues is first instituted in Sweden in 1992. The country introduced an environmental charge on nitrogen oxide (*NOx*) emissions, whose revenue was refunded to the affected plants in proportion to the amount of energy produced.[5] As a result, there was a 35% reduction in *NOx* emissions within 20 months after the implementation of the tax. Norway in January 2007, introduces a tax on *NOx* emissions, in order to meet the *NOx* emissions standards, as agreed under the *Gothenburg Protocol*. In May 2008, the tax is transformed into a Fund for investment through an agreement between the Norwegian government and business organizations resulting to further decline in *NOx* emissions. Refunding is tied directly to actual abatement costs at the firm level (expenditure based refunding); while compensations are paid to certain affected industries inter alia freight ships, fishing vessels and aircrafts. Switzerland in 2008, introduces the Carbon Dioxide ($CO_2$) incentive tax on all hydrocarbon fuels. Part of the tax revenue is redistributed to companies in proportion to their overall employee-payroll, another part is redistributed to the Swiss public via health insurance programs, and the remaining of the revenue is allocated to a 10-year building program for climate-friendlier building renovations.

With regard to the use of emission tax revenue to finance the provision of public pollution abatement, real world evidence attests to that many in countries, particularly developed ones, along with private sectors' initiatives for pollution abatement, there is substantial direct public sector involvement in so-called pollution and abatement control policies (*PAC*, e.g. Linster et al. 2007).[6] For instance, in the Netherlands the proceeds from taxes on water pollution fully finance the prevention of the country's surface waters pollution. In Germany revenue from wastewater taxation finances improvements in municipal sewage treatment whereas in France, tax revenues from environmentally related taxes finance

Footnote 3 (continued)

tosanitary measures (*SPS*s), public and private sectors quality standards, as trade barriers. Beghin et al. (2015) provide an extensive survey-study on the NTMs literature.

[4] Other environmental policy instruments such as nationally and internationally tradable emission permits, and international environmental agreements may also be opted as viable policies. Practically, however, it is not possible to cover all these policy choices in once, leaving some of them for future examination.

[5] According to Aidt (2010), and Sterner and Fredriksson (2005), emission taxation is more politically acceptable if the tax revenues are refunded to the regulated industry. Polluters pay a charge on pollution and the revenues are refunded to them in proportion to their output market share.

[6] Linster et al. (2007) report, among other things, that during 1990–2000 for most countries public expenditures accounted for about 40–60% of total PAC expenditures. Public PAC expenditures as a percentage of total PAC expenditures averaged 55% in Canada, Finland, France and Korea, 77% in Germany, 35% in Japan, and 40% in the US.

environmental projects such as waste treatment, water quality improvements and toxic pollution control.[7]

### 1.2 Review and Contribution to the Literature

Two notable results in the literature on the recycling of environmental tax revenues are that, first, for the tax revenue recycling policy to be effective in terms of firms' pollution abatement activity and emission reduction, it must be accompanied by a relatively high emissions tax (Sterner and Hoglund 2006). Second, refunding can speed up the diffusion of abatement technology if firms do not strategically influence the size of the refund (Coria and Mohlin 2013).

Recent studies conclude that, particularly in developed economies, (*i*) the effect of environmental factors is more profound than that of income growth on individual's well-being, and (*ii*) public spending for the provision of non-consumption public goods, such as ensuring environmental protection and improvement, is far more important for the well-being of their citizens, relative to public spending related to economic growth.[8] Thus, for example, higher welfare gains occur with increased public expenditures on environmental improvements, e.g., cleaner air and water, increased amount of waste recycling, rather than, e.g., on public education and health (Rehdanz and Maddison 2005; Welsch 2006; Ng 2008; Ong and Quah 2014).

Related to this real world evidence, a limited strand of the literature on *international trade and environment* considers the simultaneous abatement of pollution by the private and public sectors in trade models of perfect competition (Hatzipanayotou et al. 2005; Hadjiyiannis et al. 2009; Tsakiris et al. 2015, 2018). In this line of research, governments finance public pollution abatement activities via lump-sum taxation, or revenues from environmental taxes, or via proceeds from the sales of tradable emissions permits. To the best of our knowledge, however, the present study is the first to revisit the issue of public pollution abatement within a framework of imperfectly competitive open-economies. To this end, our study provides new insights on the effects of this scheme on exports, on conservation of the endowment of a depletable resource, on pollution reduction and welfare.

Lastly, another strand of the literature, relevant to our study, is the one considering the trade and welfare effects of *ERSs* in imperfectly competitive models of open economies. For example, Barrett (1994) examines the effects of standards as barriers to trade, suggesting that *ERSs* can enhance innovation and competitiveness of some industries, but this result rests on specific assumptions. Ulph (1996) comparing the cases where both governments use the same policy instrument, either environmental taxes or standards, concludes that *ERSs* lead to lower distortions to both environmental policy and *R&D* investment, and to significantly higher welfare in both countries relative to environmental taxes. Our study extends this literature by allowing comparison between cases where governments use different policy instruments i.e. one government imposes an environmental tax whereas the other uses an environmental standard. Lahiri and Ono (2007) derive conditions under

[7] The OECD/EU databases on environmentally related taxes illustrate numerous earmarked levies: 65 different taxes in 18 countries and 109 fees and charges in 23 countries.

[8] The economic rationale of the argument is that as real incomes grow and households can afford on their own the private provision of certain traditional public sector expenditure, e.g., health, education. Instead, they prefer increased public spending in areas of limited private provision, e.g., environmental quality, transportation, safety and security.

which a marginal change, around equilibrium, in an emission tax is welfare-superior to the emission-equivalent marginal change in an *ERS*, and those under which a change in the emission tax is emission-superior to the welfare-equivalent change in the *ERS*. They conclude that when the number of firms is fixed, lowering of the *ERS* raises welfare more than an emission-equivalent increase in the emission tax, under free entry the results can be the opposite. Antoniou et al. (2012) in a model of an international duopoly introduce uncertainty regarding the demand conditions and cost of abatement, and compare the welfare effects of *ERSs* to emission taxes when the two governments use either the same or different policy instruments, i.e., one uses an emission tax while the other applies an *ERS*. Our model of an international duopoly, while of complete certainty, introduces the use of a depletable resource, and a third instrument of environmental policy, that of public pollution abatement. We compare *ERSs* to both emission taxes and public pollution abatement in terms of their effectiveness in promoting exports, protecting the depletion of the resource, reducing emissions, and enhancing welfare when countries, thus firms, compete in imperfectly competitive markets.

Due to the complexity of most of our analytical equilibrium solutions, we perform a number of numerical calibrations, on the basis of which we also provide graphical illustrations, to solve the models and to validate the robustness of the results. Our numerical findings show that, first, revenue recycling, largely works as an export-contracting, thus, resource preserving mechanism. It always encourages private pollution abatement, but its effect on overall net pollution, i.e., the sum of domestic and transboundary production generated pollution net of firms' own abatement activity, is ambiguous. Second, public pollution abatement, under certain conditions, can be an effective environmental policy measure both in terms of promoting exports, and of reducing overall net production pollution, i.e., the sum of domestic and transboundary production generated pollution net of firms and the public sector's pollution abatement activity. In the downside it leads to higher depletion of the natural resource. *ERSs* relative to public pollution abatement largely work as an export-contracting but resource preserving mechanism, but relative to revenue recycling they work in the opposite way.

## 2 The Model

We construct a model consisting of an international duopoly, e.g., firm-country 1 and firm-country 2, and the *Rest of the World* (*ROW*). A numeraire commodity whose price, without loss of generality is fixed to unity, is produced, using clean production technologies, in all three countries under perfectly competitive conditions. For this reason, the formal treatment of the numeraire good is omitted from the rest of the analysis. Another homogeneous and freely traded good is produced, under identical production technologies and cost conditions, by the duopolists. For simplicity of the results, we assume that this product is not consumed in the two countries, thus, production of each firm tantamount to the country's exports to the *ROW*. *ROW*'s inverse demand for the internationally traded commodity is assumed to be of the form $P = B - Q$, where $P$ denotes the world price which, due to free international trade, is common to the exporting duopolists and the *ROW*. The parameter $B > 0$ captures the size of the world commodity market, and $Q = q_1 + q_2$ is the total output sold, i.e., exported, by the two firms in *ROW*'s market. Zero production and transportation costs are assumed. Output $q_i$, $i = 1, 2$, is produced by the use of a depletable natural resource, e.g., coal, which exists in fixed endowment $\overline{R_i}$ in each country. The production function of the $i$th good is given by the linear formulation $q_i = AR_i$, where $R_i$ is the amount of the resource used, and $A$ is a positive constant denoting the marginal product of the resource.[9] For simplicity, both firms face the same cost of extraction of the resource, which given the assumed linearity between $q_i$ and $R_i$, is the form $(1/2)\gamma q_i^2$, where $\gamma > 0$. Other primary factors of production such as capital, labor and land are in fixed endowments and are immobile, thus, they are omitted from the rest of the analysis. All factor markets are perfectly competitive and factors are paid the value of their marginal product.

Production generates pollution which is abated by the two firms, using an "end-of-pipe" pollution abatement technology in response to governments' environmental policies, to be discussed later on.[10] Assuming, for simplicity, that one unit of production generates one unit of pollution emissions (see e.g. Poyago-Theotoky 2007) each firm's total emissions equal production minus private pollution abatement $r_i$ $i = 1, 2$:

$$E_i(q_i, r_i) = (q_i - r_i). \tag{1}$$

Private pollution abatement is also costly to the firms. We assume a convex cost function of the form $\frac{1}{2}kr_i^2$, where larger values of the parameter $k(> 0)$ denote a less efficient private pollution abatement technology.

Production generated pollution is transboundary and affects households' utility in the two countries. A representative household in each country derives utility from the undepleted endowment of the natural resource, and from clean environment. Transboundary production pollution generated in the two countries does not affect households' welfare in the *ROW*.[11] To curb production generated pollution, the two governments implement, noncooperatively, different environmental policies, to which they commit *ex ante*. The environmental policies we consider are: (i) a emissions tax whose revenue is either refunded partly to the own emitting firm, in order to reduce its cost of pollution abatement, and partly to the country's representative household, or it is used to finance public pollution abatement; and (ii) an *ERS*. Based on the above, we examine three different regimes of pollution abatement by the two countries. *Regime I*: Country 1 implements an emissions tax, with the tax revenue being lump-sum rebated partly to the polluting firm to compensate for its pollution abatement cost, and partly to local households, while country 2 adopts an *ERS*. *Regime II*: Both countries impose emissions taxes. Country 1, however, uses the tax revenue to finance public sector pollution abatement whereas country 2 lump-sum rebates the tax revenue partly to the polluting firm, and partly to local households. *Regime III*:

[9] We assume that the resource endowment is quite high, so that it never reaches complete depletion. If this assumption does not hold, then output in each country is exogenously determined by the level of the resource endowment, i.e., $\overline{q_i} = A\overline{R_i}$.

[10] In general, when pollution is a by-product of production there are two types of technological processes of abating pollution abatement. Namely, the end-of-pipe technology and the clean technology. The first refers to equipment installed by a firm that can reduce gross emissions while keeping total output unchanged, e.g., chambers, cyclones, electrostatic precipitators, filters, and scrubbers. End-of-pipe technologies are largely used for the treatment of air emissions and waste water. The second involves a change in a firm's production process that generates less pollution per unit of output. In this study, following an extensive literature (e.g. Ulph 1996; Petrakis and Poyago-Theotoky 2002; Poyago-Theotoky 2007; Ouchida and Goto 2014), we adopt the end-of-pipe technology type of ER&D for our analysis. Another strand of the literature employs the clean production type (Petrakis and Xepapadeas 1999; Tsai et al. 2015).

[11] Even economies which probably do not generate noticeable environmental damages to the *ROW* may still have an incentive to curb the levels of their own pollution emissions. One reason can be that various pollution generated production activities create not only global pollutants, e.g., $CO_2$ emissions, but also other polluting agents which can be local in nature.

country 1 imposes an emissions tax and uses its proceeds to finance public sector pollution abatement, while country 2 adopts an *ERS*.

## 3 Regime *I*: Revenue Recycling Versus *ERS*

In this section, we consider the case where one country, e.g., country 1, imposes a revenue-recycling tax per unit of emissions. The emission tax revenue is lump-sum refunded partly to the emitting firm in a manner reducing its cost undertaking pollution abatement, and partly to the country's households. Country 2 adopts an *ERS*. Hence, pollution emissions by firm 2 cannot exceed the environmental standard set by its government. A lower (higher) *ERS* corresponds to a tighter (laxer) environmental constraint.

The profit functions of the two firms are given by:

$$\pi_1(q_1, q_2, r_1; t_1) = (B - q_1 - q_2)q_1 - t_1(q_1 - r_1) - \left[\frac{1}{2}k(r_1)^2 - \delta t_1(q_1 - r_1)\right] - \frac{1}{2}\gamma q_1^2, \tag{2}$$

$$\begin{aligned} \text{s.t. } R_1 < \overline{R_1}.\ \pi_2(q_1, q_2, r_2; s_2) \\ = (B - q_2 - q_1)q_2 - \frac{1}{2}k(r_2)^2 - \frac{1}{2}\gamma q_2^2, \\ s.t.\ q_2 - r_2 \leq s_2 \quad \text{and} \quad R_2 < \overline{R_2}. \end{aligned} \tag{3}$$

where $t_1$ and $\delta \in [0, 1)$, respectively, are the emission tax per unit of emissions, and the share of environmental tax revenue refunded to firm 1, exogenously given (see e.g. Gersbach and Requate 2004). When $\delta = 1$, firm 1 gets a full tax refund, equivalent to not paying taxes. $s_2$ is the emissions quota (*ERS*) set by the government of the country 2. Under recycling of tax revenue, firm's 1 profits are defined as the difference between revenue from sales (exports) of its output, i.e., $(B - q_1 - q_2)q_1$, minus emission taxes paid, i.e., $t_1(q_1 - r_1)$ , minus its net, after tax refund, cost of private pollution abatement, i.e., $[\frac{1}{2}k(r_1)^2 - \delta t_1(q_1 - r_1)]$ and the cost of extracting the depletable natural resource, i.e., $\frac{1}{2}\gamma q_1^2$. Firm 1 is binded in its production of $q_1$ by the resource use constraint stating that the demand for the natural resource $R_1$ cannot exceed its available fixed endowment $\overline{R_1}$. Under the *ERS*, firm's 2, profits are the difference between revenue from sales (exports) of its output, i.e., $(B - q_2 - q_1)q_2$, minus the incurred full cost of private pollution abatement, i.e., $\frac{1}{2}k(r_2)^2$, and the cost of the resource extraction, i.e., $\frac{1}{2}\gamma q_2^2$. Firm 2 is binded by the constraint of the implemented *ERS, i.e.,* $s_2$, and the resource constraint $R_2 < \overline{R_2}$.

Pollution is transboundary ($Z$) across the two countries, and it is assumed to be perfect. Overall net pollution in each country is defined as the sum of production generated pollution by the two firms net of the amount of pollution abated by the private abatement. Thus, we define:

$$Z = E_1 + E_2 = (q_1 - r_1) + (q_2 - r_2). \tag{4}$$

Such would be the case of "global warming" caused by $CO_2$ emissions and other greenhouse gases that are released during the natural-resource based polluting production process.[12]

[12] Other forms of cross-border pollution would be to specify overall pollution, net of private abatement, as $E_1 = (q_1 - r_1) + \beta_1(q_2 - r_2)$ for country 1 and $E_2 = (q_2 - r_2) + \beta_2(q_1 - r_1)$ for country 2, where

The social planners' objective is to maximize their representative households' welfare, given by the functions:

$$SW_1 = \pi_1 + (1-\delta)t_1(q_1 - r_1) - D(Z) + \left(\overline{q_1} - q_1\right)^2, \quad (5)$$

$$SW_2 = \pi_2 - D(Z) + \left(\overline{q_2} - q_2\right)^2, \quad (6)$$

where $(1-\delta)t_1(q_1 - r_1)$ is tax revenues lump-sum distributed to households in country 1. $\left(\overline{q_i} - q_i\right)^2$ captures the households' enjoyment from the undepleted amount of the natural resource, and $\overline{q_i} = A\overline{R_i}$, is the level of output corresponding to complete exhaustion of endowment of the resource in country $i$. $D(Z) = D(E_1 + E_2) = \frac{1}{2}\theta[(q_1 - r_1) + (q_2 - r_2)]^2$ captures the environmental damage of production generated transboundary pollution on households' welfare. The parameter $\theta(>0)$, assumed to be exogenous and the same for both countries, denotes the total marginal damage from unabated production generated emissions.

A two-stage pre-commitment game ensues. In the first stage, the two governments set non-cooperatively their welfare maximizing environmental policy. Government 1 chooses $t_1$, and government 2 sets $s_2$. In the second stage, taking the governments' policy choices as given, the two firms choose non-cooperatively their output quantities $q_1$, $q_2$, the levels of resource use, $R_1$, $R_2$ and the levels of private pollution abatement, $r_1$, $r_2$. The sub-game perfect Nash equilibrium of the game is solved by backward induction.[13]

### 3.1 Output Competition, Resource Use, and Pollution Abatement

Starting with the second stage of the game, firms in the two countries maximize profits given in Eqs. (2) and (3). Differentiating the profit functions with respect to $q_1$ and $q_2$, we derive the following first-order conditions:

$$\frac{\partial \pi_1}{\partial q_1} = 0 \Leftrightarrow q_1 = \frac{B - q_2 - t_1(1-\delta)}{2+\gamma}, \quad (7a)$$

$$\frac{\partial \pi_2}{\partial q_2} = 0 \Leftrightarrow q_2 = \frac{B - q_1 + ks_2}{2+k+\gamma}, \quad (7b)$$

where $\frac{\partial q_2}{\partial q_1}\big|_{firm1} = -(2+\gamma) < 0$ and $\frac{\partial q_2}{\partial q_1}\big|_{firm2} = -\frac{1}{2+k+\gamma} < 0$, respectively, are the slopes of firm 1's and firm 2's reaction functions. Solving simultaneously the first-order conditions,

Footnote 12 (continued)

$0 \leq \beta_1, \beta_2 \leq 1$ denote respectively the rates of cross-border pollution from country 2 to 1 and vice-versa. For $\beta_i = 0, i = 1, 2$, pollution is purely local, and for $\beta_1 = \beta_2 = 1$ pollution is perfectly transboundary.

[13] We assume that firms act within a framework of complete information. Cooper and Riezman (1989), and Antoniou et al. (2012), among others, introduce uncertainty, assuming that when firms maximize their profits, they are more informed about demand and costs conditions than governments are. Moreover, our analysis lies on the conjecture that each firm chooses non-cooperatively its profits maximizing level of output accounting for the output choice of the other firm, i.e., Cournot competition. Alternatively the model can be easily modified to accommodate the case of price, i.e., Bertrand competition, between the two firms. For brevity considerations, the latter is beyond the scope of the present analysis.

we obtain the profit maximizing levels of output for the two firms as functions of the policy instruments $t_1$and $s_2$, and the parameters of the model. That is:[14]

$$q_1 = \frac{B(1+k+\gamma) - ks_2 - (2+k+\gamma)(1-\delta)t_1}{k(2+\gamma) + (1+\gamma)(3+\gamma)}, \tag{8}$$

$$q_2 = \frac{B(1+\gamma) + (1-\delta)t_1 + ks_2(2+\gamma)}{k(2+\gamma) + (1+\gamma)(3+\gamma)}. \tag{9}$$

where $\frac{\partial q_1}{\partial t_1} < 0$, $\frac{\partial q_1}{\partial s_2} < 0$, $\frac{\partial q_2}{\partial s_2} > 0$ and $\frac{\partial q_2}{\partial t_1} > 0$. A higher emissions tax by country 1 lowers output and exports of the country, and it increases output and exports of country 2. A tighter *ERS* by country 2, lowers its output and exports, and it raises those of country 1. Thus, laxer environmental policies in terms of either a lower emission tax by country 1 or/and a looser *ERS* by country 2, induce rent-shifting incentives for both countries via higher production and exports.

The levels of private pollution abatement of the two firms are derived from the following first order conditions:

$$\frac{\partial \pi_1}{\partial r_1} = 0 \Leftrightarrow r_1 = \frac{(1-\delta)}{k} t_1, \quad \text{and} \tag{10}$$

$$r_2 = q_2 - s_2 = \frac{B(1+\gamma) - (1+\gamma)(3+\gamma)s_2 + (1-\delta)t_1}{k(2+\gamma) + (1+\gamma)(3+\gamma)}, \tag{11}$$

where $\frac{\partial r_i}{\partial t_1} > 0, \frac{\partial r_i}{\partial \delta} < 0$, and $\frac{\partial r_2}{\partial s_2} < 0$, $i = 1, 2$. That is, (i) an increase in the environmental tax by country 1 motivates both firms to undertake more private pollution abatement, (*ii*) the higher is the share ($\delta$) of refunded tax revenues to the emitting firm 1, the lower is both firms' private pollution abatement, and (*iii*) the adoption of a stricter environmental standard by the government in country 2, lowers the level of private pollution abatement undertaken by firm 2.

Finally, the levels of resource use by the two firms, are, $R_i = q_i/A$, where $q_i$s are the profit maximizing levels of outputs in Eqs. (8) and (9). In conjunction with these equations, it can be easily deduced that a laxer environmental policy by one country, either in terms of a lower emission tax or/and a looser *ERS* leads to "resource depletion" locally, but to "resource savings" in the other. Thus, a higher emissions tax by country 1lowers the resource use in the country, but it intensifies the resource use in country 2. A similar result holds for a tighter *ERS* by country 2.

[14] In order to ensure that $q_1 > 0$ and $q_2 > 0$, the conditions $t_1 < \frac{B(1+k+\gamma)-ks_2}{(2+k+\gamma)(1-\delta)}$ and $s_2 > \frac{-B(1+\gamma)-t_1(1-\delta)}{2(k+\gamma)}$ must hold. The second-order conditions for the maximization problems i.e. $\frac{\partial^2 \pi_1}{\partial q_1^2} = -(2+\gamma) < 0$ and $\frac{\partial^2 \pi_2}{\partial q_2^2} = -(2+k+\gamma) < 0$ and the stability condition $\Delta = k(2+\gamma) + (1+\gamma)(3+\gamma) > 0$ are also satisfied since $k > 0$ and $\gamma > 0$.

### 3.2 Nash Equilibrium: Welfare and Optimal Policy Levels

Continuing with the first stage of the game, country 1 chooses non-cooperatively $t_1$ and country 2 chooses non-cooperatively $s_2$, so each to maximize its representative household's welfare. In making this decision, each government accounts for the two firms' reaction to their welfare maximizing policy choices. Substituting Eqs. (2) and (3) in Eqs. (5) and (6), the two countries' welfare functions are as follows:

$$SW_1(q_1, q_2, r_1, r_2; t_1, s_2) = (B - q_1 - q_2)q_1 - \frac{1}{2}kr_1^2 - \frac{1}{2}\gamma q_1^2 - \frac{1}{2}\theta[(q_1 - r_1) + (q_2 - r_2)]^2 + \left(\overline{q_1} - q_1\right)^2, \text{ and} \tag{12}$$

$$SW_2(q_1, q_2, r_1, r_2; t_1, s_2) = (B - q_2 - q_1)q_2 - \frac{1}{2}kr_2^2 - \frac{1}{2}\gamma q_2^2 - \frac{1}{2}\theta[(q_1 - r_1) + (q_2 - r_2)]^2 + \left(\overline{q_2} - q_2\right)^2. \tag{13}$$

Substituting $q_1$, $q_2$, $r_1$ and $r_2$, from Eqs. (8), (9), (10) and (11), we obtain the welfare levels as functions of the policy instruments $t_1$ and $s_2$, and of the parameters of the model. Setting $\frac{dSW_1}{dt_1} = 0$ and $\frac{dSW_2}{ds_2} = 0$, and solving simultaneously these first order conditions, we obtain the two countries' reaction functions, and the Nash equilibrium emission tax for country 1, and the Nash equilibrium *ERS* for country 2 as functions of the parameters $B, \delta, k, \gamma, \theta, \overline{q_1}$ and $\overline{q_2}$:[15]

$$t_1^N = f_1(\delta, B, k, \gamma, \theta, \overline{q_1}, \overline{q_2}), \qquad s_2^N = f_2(B, k, \gamma, \theta, \overline{q_1}, \overline{q_2}). \tag{14}$$

Substituting $t_1^N$ and $s_2^N$ into (8), (9), ( 10) and (11), we obtain the Nash equilibrium levels of firms' outputs, i.e. exports, of private pollution abatement, of resource use, and of gross emissions as functions of $B, k, \gamma, \theta, \overline{q_1}, \overline{q_2}$[16] and $A$. The Nash equilibrium level of overall net pollution in each country is $Z^N = q_1^N - r_1^N + q_2^N - r_2^N$.[17]

After substituting the equilibrium values $q_1^N$, $q_2^N$, $r_1^N$, and $r_2^N$ into Eqs. (12) and (13 ), the Nash equilibrium welfare levels for countries 1 and 2 are given respectively as follows:

$$SW_1^N = w_1(B, k, \gamma, \theta, \overline{q_1}, \overline{q_2}) \text{ and } SW_2^N = w_2(B, k, \gamma, \theta, \overline{q_1}, \overline{q_2}). \tag{15}$$

Due to the complexity of the analytical equilibrium solutions, we proceed to obtain numerical results. In particular we obtain numerically the optimal values of $t_1^N$ and $s_2^N$, and of

[15] Due to their complexity, the analytical expressions for the reaction functions, the Nash equilibrium tax for country 1 and the Nash equilibrium *ERS* for country 2 are relegated to an online *Appendix***.** Moreover, for a given value of $\delta$, there is a unique optimal value of $t_1^N$. The optimal value of the environmental standard imposed in country 2, $s_2^N$, is always independent of $\delta$.

[16] For example, for firm 1 we obtain $q_1^N = q_1^N(B, k, \gamma, \theta, \overline{q_1}, \overline{q_2})$, $r_1^N = r_1^N(B, k, \gamma, \theta, \overline{q_1}, \overline{q_2})$, $E_1^N = q_1^N - r_1^N$. Similar results are obtained for firm 2. Furthermore, note that by substituting (14) into (8), (9), (10 ) and (11), $\delta$ cancels out from all optimal values. Thus, the equilibrium results hold for any $\delta$ chosen by government in country 1.

[17] Given the Cournot-Nash competition between the two firms, substituting the Nash equilibrium values $q_1^N$, $q_2^N$ into the world inverse demand function $P = B - \left(q_1 + q_2\right)$, determines the Nash equilibrium world price $P^N$ of the freely tradable commodity. $P^N$ is the unique Nash equilibrium price both for the two exporting countries and the importing *ROW*.

**Table 1** Parameter values used in the model

| Description | Symbol | Value | Range | Source |
|---|---|---|---|---|
| Demand parameter (size of the world commodity market) | $B$ | 30 | $(0, +\infty)$ | Farzin (2004) |
| Cost of private pollution abatement | $k$ | 2 | $(0, +\infty)$ | Farzin (2004) |
| Cost of natural resource extraction | $\gamma$ | 1.1 | $(0, +\infty)$ | International Energy Agency, natural resource refers to hard coal, expressed in dollars per GJ |
| Marginal product of natural resource | $A$ | 1 | $(0, +\infty)$ | International Energy Agency, natural resource refers to hard coal |
| Environmental damage parameter from unabated emissions | $\theta$ | 1 | $(0, +\infty)$ | van der Ploeg and Withagen (2012); Farzin (2004), expressed in Gt CO2 |
| Share of environmental tax revenue refunding | $\delta$ | 0.3 | $[0, 1)$ | Sterner and Hoglund (2006) |
| Maximum level of fixed endowment of natural resource | $\bar{R}$ | 10 | $(0, +\infty)$ | International Energy Agency, natural resource refers to proven hard coal reserves worldwide, expressed in million short tons (average per supply country) |
| Cost of Government's (engaged in public pollution abatement) efficiency per unit of public pollution abatement | $c$ | 0.3 if low, 0.8 if high | $(0, 1]$ | Own indicative values within the range |

The table reports the chosen parameter values used in our numerical analysis and their respective sources

$q_1^N$, $q_2^N$, $r_1^N$, $r_2^N$, $R_1^N$, $R_2^N$, $E_2^N$, $E_2^N$, $SW_1^N$ and $SW_2^N$, using a wide set of *plausible* values for the parameters of the model. Table 1 summarizes all the parameters used in the model's parameterization as well as their sources of origin. The results are discussed in the following section.

### 3.3 Main Results and Numerical Simulations

The optimal values for the variables of the model for the three regimes of pollution abatement and specific values for its parameters, are presented in Tables 2 and 3. Relevant to *Regime I* are the results reported in Column *A* of the tables.[18] On the basis of these findings, we state the following *Result*:

**Result 1** Consider an international duopoly where production generates transboundary pollution. To regulate emissions, one country implements an emission tax revenue recycling scheme, while the other adopts an *ERS*. Then, at Nash equilibrium, independently of the parameter values of the model, exports and welfare are always higher under the environmental standard, whereas a firm's level of pollution abatement is higher, and the levels of production emissions and resource use are lower under a revenue-recycling emission tax.

**Discussion** According to the results of column *A* in Tables 2 and 3, the *ERS* works as an export promoting policy, as country 2's production, and consequently, exports to the *ROW* are higher to those of country 1. In the downside, however, the *ERS* leads to a more extensive depletion of the resource, relative to the revenue-recycling emission tax. Revenue recycling fosters the undertaking of pollution abatement activity by firms, independently of the parameter values of the model. This result is in line with Coria and Mohlin (2013) who conclude that emission tax refunding can accelerate the diffusion of abatement technology if firms cannot strategically influence the size of the refund.[19] Thus, the undertaking of pollution abatement, induced by revenue recycling to the polluting firm, reduces emissions more than the *ERS* does.[20]

Several policy implications emerging from the above numerical calibrations can be derived. Under the conditions of this regime, when (trade) policies of direct or indirect export subsidies are difficult to implement either because of revenue considerations by governments or because of binding international trade agreements, and instead environmental measures are implemented in order to expand exports in international markets, then, the adoption of an *ERS* dominates the adoption of a revenue-recycling emission tax. If, however, the objectives of environmental policies are considerations, such as, the prevention

[18] A graphical illustration of these results for various parameter values is presented in an online Appendix.

[19] For the recycling policy to be effective in terms of firms' pollution abatement activity and emission reduction, it must be accompanied by a relatively high tax. Sterner and Hoglund (2006) demonstrate that significant abatement effects can be achieved if only a sufficiently high tax is charged. Our findings are in line with this result, since in our analysis the recycling tax is found to be significantly higher than the *ERS*. A real-world example along these lines is the Swedish charge on nitrogen oxides and its successful effects underpin this result.

[20] In order to assess the robustness of the above results, we perform a number of sensitivity experiments of the numerical findings to the chosen parameter values, which we report in an online *Appendix*. These do in fact verify the aforementioned results.

of the over-use of a natural resource or the reduction of the levels of production generated emissions, then a revenue-recycling emission tax dominates the choice of an *ERS*. Welfare-wise, an *ERS* is superior to a revenue-recycling emission tax.

The above discussion and numerical results relate to when the two countries choose non-cooperatively their environmental policies, in order to maximize own welfare, without accounting for the externalities, e.g., transboundary pollution, inflicted upon the other country. In light of this, numerical calibrations are performed assuming that each country chooses its policy instrument cooperatively, i.e., so as to maximize the countries' joint welfare. Thus, country 1 chooses $\left(t_1\right)$ and country 2 chooses $\left(s_2\right)$ so as to maximize $SW_1 + SW_2$. The results of this numerical exercise presented in Table 4, confirm the well know standard result. The Nash equilibrium environmental policies are laxer than the corresponding cooperative ones, i.e., $t_1^N < t_1^C$ and $s_2^N > s_2^C$, where $t_1^C$ and $s_2^C$ are, respectively, the cooperative emission tax rate chosen by country 1, and the cooperative level of the *ERS* chosen by country 2.

## 4 Regime *II*: Public Pollution Abatement Versus Revenue Recycling

Now let both countries control production-generated pollution emissions by imposing emissions taxes, $t_1$ and $t_2$, respectively. However, the emission tax revenue is dispersed differently by the two governments. In country 1 the government retains this revenue in order to purchase, at a constant world price, an internationally traded good, in quantity $g$, which then it uses for pollution abatement (Hadjiyiannis et al. 2009). Assuming that the government maintains an active, balanced, budget constraint, we have[21]:

$$g = t_1(q_1 - r_1). \tag{16}$$

In country 2 the government follows a scheme of revenue-recycling of the emission tax revenue, at rates $\delta$ and $(1-\delta)$, respectively, to its emitting firm and representative household. As a result of the governments' environmental policies, the levels of production emissions are again given by Eq. (1), while overall net pollution in each country is defined as:

$$Z = \left[\left(q_1 - r_1\right) + \left(q_2 - r_2\right) - cg\right], \tag{17}$$

where the parameter $0 < c \le 1$ captures country 1's government efficiency per unit of public pollution abatement. All other analytical features are the same as in *Regime I*.

The profit functions of the two firms are given as follows:

$$\begin{aligned} \pi_1(q_1, q_2; r_1, t_1) = & (B - q_1 - q_2)q_1 - t_1(q_1 - r_1) - \frac{1}{2}k(r_1)^2 - \frac{1}{2}\gamma q_1^2, \\ & s.t. \quad R_1 < \overline{R_1} \end{aligned} \tag{18}$$

[21] This specification implies a constant unit cost of pubic pollution abatement which is normalized to unity. Alternatively one may consider non-linear abatement technologies, e.g., $f(g)$, where $f_g > 0$ denotes the public sector's effectiveness in abating pollution. In our model, we assume that $f_g = f^*_{g^*} = 1$.

**Table 2** Main results—comparing different models—low cost of extraction

| Variable | Recycling versus ERS | Public abatement versus recycling | | Public abatement versus ERS | |
|---|---|---|---|---|---|
| | (A) | (B) | (C) | (D) | (E) |
| $t_1$ | 10.980 | 2.614 | 1.395 | 5.181 | 2.026 |
| $t_2$ | | 10.492 | 9.208 | | |
| $s_2$ | 2.820 | | | 4.004 | 4.722 |
| $r_1$ | 3.843 | 1.307 | 0.697 | 2.590 | 1.013 |
| $r_2$ | 3.132 | 3.672 | 3.222 | 2.275 | 1.645 |
| $q_1$ | 5.277 | 7.229 | 7.563 | 5.980 | 6.969 |
| $q_2$ | 5.954 | 4.976 | 5.158 | 6.280 | 6.367 |
| $R1$ | 5.277 | 7.229 | 7.563 | 5.980 | 6.969 |
| $R_2$ | 5.954 | 4.976 | 5.158 | 6.280 | 6.367 |
| $SW_1$ | 82.207 | 87.053 | 94.443 | 76.044 | 84.979 |
| $SW_2$ | 89.753 | 82.500 | 85.030 | 96.114 | 93.764 |
| $E_1$ | 1.434 | 5.922 | 6.865 | 3.389 | 5.956 |
| $E_2$ | 2.821 | 1.304 | 1.935 | 4.004 | 4.722 |
| $Z$ | 4.250 | 2.582 | 1.135 | 2.125 | 1.023 |

In all numerical experiments we assume that the share of refunding $\delta = 0.3$, the demand parameter $B = 30$ , the cost of private abatement $k = 2$, the cost of extraction $\gamma = 1.1$, the marginal product of extraction $A$ and the damage parameter in the social welfare function $\theta$ take the value 1. Column (A) reports our results when country 1 follows a revenue recycling policy while country 2 imposes an ERS (case 1). Column (B) shows the results when the first government engages in public pollution abatement, while country 2 employs revenue recycling (case 2) and the efficiency of the government engaging in abatement is relatively low taking the value $c = 0.3$. Column (C) presents the results when the first government engages in public pollution abatement, while country 2 employs revenue recycling (case 2) and the efficiency of the government engaging in abatement takes the value $c = 0.8$. Column (D) shows the results when the first government uses public pollution abatement whilst the second one uses an ERS (case 3) when the efficiency of the government engaging in abatement is relatively low taking the value $c = 0.3$.Column (E) shows the results when the first government uses public pollution abatement whilst the second one uses an ERS (case 3) when the efficiency of the government engaging in abatement is relatively high taking the value $c = 0.8$

$$\pi_2(q_1, q_2, r_2; t_2) = (B - q_2 - q_1)q_2 - t_2(q_2 - r_2) - \left[\frac{1}{2}k(r_2)^2 - \delta t_2(q_2 - r_2)\right] - \frac{1}{2}\gamma q_2^2, \quad s.t. \quad R_2 < \overline{R_2}. \tag{19}$$

The social planners' objective is to maximize their representative households' welfare, by choosing the optimal rates of environmental taxes, $t_1$ and $t_2$, respectively. Social welfare in the two countries is given by the functions:

$$SW_1 = \pi_1 - D(Z) + \left(\overline{q_1} - q_1\right)^2, \tag{20}$$

**Table 3** Main results—comparing different models—high cost of extraction

| Variable | Recycling versus ERS | Public abatement versus recycling | | Public abatement versus ERS | |
|---|---|---|---|---|---|
| | (A) | (B) | (C) | (D) | (E) |
| $t_1$ | 7.384 | 3.633 | 1.765 | 3.485 | 1.777 |
| $t_2$ | | 5.795 | 5.193 | | |
| $s_2$ | 1.042 | | | 1.467 | 1.906 |
| $r_1$ | 2.584 | 1.816 | 0.882 | 1.742 | 0.888 |
| $r_2$ | 2.524 | 2.028 | 1.817 | 2.173 | 1.809 |
| $q_1$ | 3.543 | 3.778 | 4.086 | 3.812 | 4.084 |
| $q_2$ | 3.567 | 3.694 | 3.712 | 3.640 | 3.716 |
| $R1$ | 3.543 | 3.778 | 4.086 | 3.812 | 4.084 |
| $R_2$ | 3.567 | 3.694 | 3.712 | 3.640 | 3.716 |
| $SW_1$ | 88.993 | 83.732 | 85.688 | 83.984 | 85.675 |
| $SW_2$ | 89.196 | 90.466 | 90.915 | 90.357 | 90.934 |
| $E_1$ | 0.959 | 1.962 | 3.203 | 2.069 | 3.195 |
| $E_2$ | 1.042 | 1.665 | 1.895 | 1.467 | 1.906 |
| $Z$ | 2.002 | 1.489 | 0.572 | 1.372 | 0.558 |

In all numerical experiments we assume that the share of refunding $\delta = 0.3$, the demand parameter $B = 30$ , the cost of private abatement $k = 2$, the cost of extraction $\gamma = 4.0$, the marginal product of extraction $A$ and the damage parameter in the social welfare function $\theta$ take the value 1. Column (A) reports our results when country 1 follows a revenue recycling policy while country 2 imposes an ERS (case 1). Column (B) shows the results when the first government engages in public pollution abatement, while country 2 employs revenue recycling (case 2) and the efficiency of the government engaging in abatement is relatively low taking the value $c = 0.3$. Column (C) presents the results when the first government engages in public pollution abatement, while country 2 employs revenue recycling (case 2) and the efficiency of the government engaging in abatement takes the value $c = 0.8$. Column (D) shows the results when the first government uses public pollution abatement whilst the second one uses an ERS (case 3) when the efficiency of the government engaging in abatement is relatively low taking the value $c = 0.3$.Column (E) shows the results when the first government uses public pollution abatement whilst the second one uses an ERS (case 3) when the efficiency of the government engaging in abatement is relatively high taking the value $c = 0.8$

$$SW_2 = \pi_2 + (1-\delta)t_2(q_2 - r_2) - D(Z) + \left(\overline{q_2} - q_2\right)^2, \tag{21}$$

where $D(Z) = D\left(E_1 + E_2 - cg\right) = \frac{1}{2}\theta[(q_1 - r_1) + (q_2 - r_2) - cg]^2$ is the environmental damage due to local and transboundary pollution, net of firms and public sector's abated pollution. The government in country 1 must also satisfy its budget constraint in Eq. (16).

We consider a pre-commitment game carried-out in two stages. In the first stage, both governments choose non-cooperatively the welfare maximizing emission taxes $t_1$ and $t_2$. In the second stage, taking the governments' policy choices as given, firms 1 and 2 decide on output quantities $q_1$ and $q_2$, and levels of resource use $R_i$ and of pollution abatement $r_i$. The sub-game perfect Nash equilibrium of the game is solved by backward induction.

**Table 4** Comparison of nash and cooperative equilibrium values

| | Recycling versus ERS | Public abatement versus recycling | | Public abatement versus ERS | |
|---|---|---|---|---|---|
| | | $c = 0.3$ | $c = 0.8$ | $c = 0.3$ | $c = 0.8$ |
| $\gamma = 1.1$ | $t_1^N = 10.98 < t_1^C = 12.25$ | $t_1^N = 2.61 < t_1^C = 3.59$ | $t_1^N = 1.39 < t_1^C = 1.44$ | $t_1^N = 5.18 < t_1^C = 9.13$ | $t_1^N = 2.02 < t_1^C = 8.25$ |
| | | $t_2^N = 10.49 < t_2^C = 10.66$ | $t_2^N = 9.20 < t_2^C = 9.95$ | | |
| | $s_2^N = 2.82 > s_2^C = 0.94$ | | | $s_2^N = 4.00 > s_2^C = 2.10$ | $s_2^N = 4.72 > s_2^C = 4.55$ |
| | $Z^N = 4.25 > Z^C = 1.86$ | $Z^N = 2.58 > Z^C = 0.91$ | $Z^N = 1.13 > Z^C = 0.43$ | $Z^N = 2.12 > Z^C = 0.31$ | $Z^N = 1.02 > Z^C = 0.52$ |
| $\gamma = 4$ | $t_1^N = 7.38 < t_1^C = 8.32$ | $t_1^N = 3.63 < t_1^C = 4.09$ | $t_1^N = 1.76 < t_1^C = 1.80$ | $t_1^N = 3.48 < t_1^C = 3.90$ | $t_1^N = 1.77 < t_1^C = 1.80$ |
| | | $t_2^N = 5.79 < t_2^C = 6.75$ | $t_2^N = 5.19 < t_2^C = 5.78$ | | |
| | $s_2^N = 1.04 > s_2^C = 0.53$ | | | $s_2^N = 1.46 > s_2^C = 1.10$ | $s_2^N = 1.90 > s_2^C = 1.62$ |
| | $Z^N = 2.00 > Z^C = 1.07$ | $Z^N = 1.48 > Z^C = 0.84$ | $Z^N = 0.57 > Z^C = 0.20$ | $Z^N = 1.37 > Z^C = 0.80$ | $Z^N = 0.55 > Z^C = 0.20$ |

In all numerical experiments we assume that the share of refunding $\delta = 0.3$, the demand parameter $B = 30$ , the cost of private abatement $k = 2$, the marginal product of extraction $A$ and the damage parameter in the social welfare function $\theta$ take the value 1. These numerical results are indicative. All the numerical simulations for all three regimes under the cooperative scenario have been performed and the relevant results are relegated to an online Appendix

### 4.1 Output Competition, Resource Use, and Private Pollution Abatement

In the second stage the two firms chose outputs to maximize profits given the non-cooperative choice of $t_1$and $t_2$ by their governments to regulate pollution. Maximizing the profit functions (18) and (19) with respect to $q_1$ and $q_2$ we obtain the two firms' reaction functions, respectively given as follows[22]:

$$B - q_2 - t_1 = q_1(2 + \gamma), \tag{22a}$$

$$B - q_1 - t_2(1 - \delta) = q_2(2 + \gamma) \tag{22b}$$

Solving the above system, yields the Cournot-Nash equilibrium values of outputs as functions of $t_1$and $t_2$, and the parameters of the model:

$$q_1 = \frac{B(1 + \gamma) + t_2(1 - \delta) - t_1(1 + \gamma)}{3 + 4\gamma + \gamma^2}, \text{ and} \tag{23a}$$

$$q_2 = \frac{B(1 + \gamma) + t_1 - t_2(1 - \delta)(2 + \gamma)}{3 + 4\gamma + \gamma^2}, \tag{23b}$$

where $\frac{\partial q_i}{\partial t_i} < 0, i = 1, 2$ and $\frac{\partial q_i}{\partial t_j} > 0, i = 1, 2, j = 2, 1$. Output, thus, exports of each firm fall with a higher (lower) own (foreign) emissions tax. This result attests to a strategic substitutability between $t_1$ and $t_2$. Also, $\frac{\partial q_1}{\partial \delta} < 0$, and $\frac{\partial q_2}{\partial \delta} > 0$. When country 2 refunds a larger share of the emission tax revenue to its own polluting firm, production and exports increase by country 2, whilst they decline by country 1.

Firms' levels of pollution abatement are given by the first-order-conditions $\frac{\partial \pi_i}{\partial r_i} = 0$. Thus, we obtain[23,24]:

$$r_1 = \frac{t_1}{k} \quad \text{and} \quad r_2 = \frac{t_2(1 - \delta)}{k}, \tag{24}$$

where $\frac{\partial r_1}{\partial t_1} = \frac{1}{k} > 0$ and $\frac{\partial r_2}{\partial t_2} = \frac{1-\delta}{k} > 0$. Pollution abatement by both firms rises the higher is the emission tax rate, and the lower is the cost of undertaking this activity ($k$). Moreover, firm 2 undertakes more pollution abatement with a higher share of emission tax revenue ($\delta$) refunded to it by the government.

Lastly, the optimal levels of resource use in the two countries are given by $R_1 = \frac{q_1}{A}$ and $R_2 = \frac{q_2}{A}$, respectively, where $q_1$ and $q_2$ are the profit maximizing levels of firms' outputs in Eqs. (23a)–(23b). In this case, optimal resource use in each country declines with the own emission tax and it increases with a higher emission tax by the other country. This result

[22] Note that, since $\gamma > 0$, both the second-order conditions, i.e., $\frac{\partial^2 \pi_i}{\partial q_i^2} = -(2 + \gamma) < 0$, and the stability condition, i.e., $\Delta = (1 + \gamma)(3 + \gamma) > 0$ , hold throughout the section. Furthermore, in order to ensure that $q_i > 0$, the conditions $t_1 < \frac{1}{2}[B + t_2(1 - \delta)]$ and $t_2 < \frac{B+t_1}{2(1-\delta)}$ must also be satisfied. Otherwise, the two firms have no incentives to produce.

[23] Since $k > 0$, the second-order conditions $\partial^2 \pi_i / \partial r_i^2 = -k < 0, i = 1, 2$ hold throughout the paper, and so the conditions for interior solutions are satisfied.

[24] Non-negativity of outputs means that the conditions $t_1 < \frac{1}{2+\gamma}[B(1 + \gamma) + t_2(1 - \delta)]$ and $t_2 < \frac{B(1+\gamma)+t_1}{(2+\gamma)(1-\delta)}$ must be satisfied. Substituting these conditions into Eq. (24), yields that the conditions $r_1 < \frac{1}{(2+\gamma)k}[B(1 + \gamma) + t_2(1 - \delta)]$ and $r_2 < \frac{B(1+\gamma)+t_1}{k(2+\gamma)}$ must also hold.

too, attests to the strategic substitutability between the two tax rates, and the rent shifting of emission tax policies in the two countries.

### 4.2 Nash Equilibrium: Welfare and Optimal Emission Taxes

In the first stage, each government chooses non-cooperatively its welfare maximizing emission tax, accounting for both firms' reaction to its environmental policy.

Using Eqs. (20) and (21), the two countries' welfare functions, respectively, are written as:

$$\begin{aligned} SW_1(q_1, q_2, r_1, r_2; t_1, t_2) &= (B - q_1 - q_2)q_1 - t_1(q_1 - r_1) - \frac{1}{2}kr_1^2 \\ &- \frac{1}{2}\gamma q_1^2 - \frac{1}{2}\theta[(q_1 - r_1) + (q_2 - r_2) - cg]^2 + \left(\overline{q_1} - q_1\right)^2, \text{ and,} \end{aligned} \tag{25}$$

$$\begin{aligned} SW_2(q_1, q_2, r_1, r_2; t_1, t_2) &= (B - q_2 - q_1)q_2 - t_2(q_2 - r_2) - [\frac{1}{2}kr_2^2 - \delta t_2(q_2 - r_2)] - \frac{1}{2}\gamma q_2^2 \\ &+ (1-\delta)t_2(q_2 - r_2) - \frac{1}{2}\theta[(q_1 - r_1) + (q_2 - r_2) - cg]^2 + \left(\overline{q_2} - q_2\right)^2. \end{aligned} \tag{26}$$

Substituting $q_1$, $q_2$, $r_1$ and $r_2$, from the Eqs. (23a)–(23b) and (24), we obtain the welfare levels in countries 1 and 2 as functions of, among other things, the environmental taxes $t_1$ and $t_2$. However, the associated first-order conditions ($\partial SW_1/\partial t_1 = 0$ and $\partial SW_2/\partial t_2 = 0$) cannot be solved analytically. We therefore proceed to obtain numerical results, in particular to obtain numerically the optimal values of $t_1$ and $t_2$ for a wide set of values for the parameters of the model. Table 1 summarizes all the parameters used in the model's calibration as well as their sources of origin.

### 4.3 Main Results and Numerical Simulations

*Columns B* and *C* of Tables 2 and 3 report the results of the numerical simulations relevant to Regime *II*. Tables 2 and 3 are designed for a low and a high extraction cost respectively. *Column B* reports the Nash equilibrium values of the variables of the model for low values of the parameter *c*, implying a relatively inefficient public sector in abating pollution. *Column C* reports the corresponding Nash equilibrium values for high values of *c*, implying a relatively efficient public sector in abating pollution emissions. The diagrammatic illustration of these results is presented in the figures of the online Appendix.

**Proposition 1** *Consider an international duopoly where production generates transboundary pollution, and countries regulate polluting emissions by imposing emission taxes. One country uses a public pollution abatement scheme financed via emission tax revenue, while the other adopts a revenue-recycling scheme. Based on the numerical simulations, we state the following results:*

**Result 2** Independently of the public sector's efficiency in abating pollution, a public pollution abatement scheme vis-à-vis an environmental tax revenue-recycling scheme, promotes exports leading to higher levels of resource use, and discourages private abatement by the local firm. Revenue recycling fosters the undertaking of pollution abatement activity by firms.

**Result 3** The more efficient country 1's government is in abating pollution, the lower is the level of overall net pollution ($Z$) in each country relative to local net pollution $\left(E_1\right)$ and $\left(E_2\right)$, respectively, generated by its own firm. The less efficient country 1's government is in abating pollution, then, the level of overall net pollution ($Z$) in country 1 is still lower than the level of locally generated production pollution $\left(E_1\right)$, but in country 2 overall net pollution ($Z$) is higher than the level locally generated production pollution $\left(E_2\right)$.

**Result 4** Welfare-wise, independently of the public sector's efficiency in abating pollution, a public pollution abatement scheme is a more effective policy, vis-à-vis an environmental tax revenue-recycling scheme, the lower is the cost of the resource extraction $\gamma$. The opposite result holds when the cost of the resource extraction is high.

**Discussion** *Result* 2: According to our numerical findings, public pollution abatement, financed via emission tax revenue, is an export promoting policy, even if the government is relatively inefficient in abating pollution. This leads to higher levels of depletion of the natural resource. Since the government of country 1 "steps-in" to abate pollution, the local firm has a lower incentive in undertaking its own abatement activity, i.e., $r_1$. As a result, net production pollution by local firm 1 ($E_1$), rises. In country 2 since, by the reaction functions in Eqs. (22a)–(22b), $\frac{dq_2}{dq_1} < 0$, firm 2, reduces its own production, thus exports. Moreover, given that the government rebates part of the emission tax revenue to firm 2 in order to reduce its cost of pollution abatement, then, the latter "steps-up" its own private pollution abatement activity, i.e., $r_2$. As a result, net production pollution by firm 2, i.e., $E_2$, falls independently of the parameter values of the model. This result is again in line with Coria and Mohlin (2013) who conclude that emission tax refunding can speed up the diffusion of abatement technology if firms cannot strategically influence the size of the refund. Furthermore, in order for the recycling policy to be effective in terms of firms' pollution abatement activity, it must be accompanied by a high tax. This finding is also in line with Sterner and Hoglund (2006) who demonstrate that significant abatement effects could be achieved if only a sufficiently high tax is charged.[25] We also observe that a sufficiently high revenue recycling tax, motivates firms to undertake increased abatement activity, reducing firm's polluting emissions. Thus, since firm 2's pollution abatement activity is higher than firm 1's, firm 2's net pollution is lower.

*Result* 3: The numerical simulations indicate that in country 1 independently of the degree of its government's efficiency to abate pollution, the level of overall net pollution, i.e., $Z = E_1 + E_2 - cg$ , is lower than the level of emissions $\left(E_1\right)$ generated by the local firm, but it may be higher than the level of emissions $\left(E_2\right)$ generated by the firm 2 in the other country. Intuitively, on the one hand, in country 1 the "stepped-up" pollution abatement by the government in conjunction with lower net production pollution by firm 2 outweigh the increase in net production pollution $E_1$ by the local firm. As a result, in country 1, overall net production pollution is lower than net production pollution by firm 1, i.e., $Z = E_1 + E_2 - cg < E_1$. In this case, this, also holds for country 2,

[25] A real-world example is the Swedish charge on nitrogen oxides and its successful effects in terms of lowering the levels of pollution emissions underpin this result.

i.e., its overall net production pollution also falls, i.e., $Z = E_1 + E_2 - cg < E_2$. If, however, country 1's government is relatively inefficient in abating pollution, then, in country 2, $Z = E_1 + E_2 - cg > E_2$. Thus, in our framework, the efficiency of country 1's government in abating pollution is pivotal in correcting environmental problems due to transboundary pollution across countries.

*Result* 4: In conjunction with *Results* 2 and 3, when the cost of resource extraction $\gamma$ is low, public pollution abatement in addition to being of higher-yield in terms of promoting exports, it is also more effective welfare-wise compared to a tax revenue-recycling scheme. When, however, $\gamma$ is relatively high, while public pollution abatement continues to be more effective in promoting exports, an emission tax revenue-recycling scheme is more effective in enhancing welfare. In conjunction to other studies which conclude that higher welfare gains occur with increased public expenditures on environmental improvements (e.g. Rehdanz and Maddison 2005; Welsch 2006; Ng 2008; Ong and Quah 2014), our numerical results validate this finding only when the cost of resource extraction to the firms is low. Else, welfare-wise the tax revenue-recycling scheme dominates a regime of public sector pollution abatement.[26]

Policy implications emerging from the above numerical calibrations can be as follows. When (trade) policies of direct or indirect export subsidies are difficult to implement either because of revenue considerations by governments, or because of binding international trade agreements, and governments adopt an emissions tax, then, in regard to exports promotion, it is preferable for the government to use the emission tax revenue to finance the provision of public abatement activity rather than to rebate it to its local firm in order to lower the latter's cost of undertaking abatement activity. Furthermore, for the country adopting public pollution abatement overall net cross-border pollution is lower to the level under a tax revenue-recycling regime, independently of whether the government is efficient or not in its pollution abatement activity.

Given that tax revenue-financed public pollution abatement increases a country's, e.g., here country 1, exports, the policy may turn to a "beggar-thy-neighbor" state for country 2 when the latter adopts a tax revenue-recycling policy. According to our numerical results, this is the case when country 1's government is relatively inefficient in its pollution abatement activity, thus, for country 2 not only exports fall but also overall net pollution is higher.

If both countries were to pursue tax revenue-financed public pollution abatement, and assuming that their governments are equally efficient in this activity, then, our numerical calibrations indicate that (i) the Nash equilibrium tax in the two countries is the same, (ii) overall net pollution in the two countries is lower, and (iii) the two countries split equally the world market for their (homogeneous) exportable good.[27]

Following the analysis of *Regime I*, numerical calibrations are performed assuming that each country chooses its emissions tax $\left(t_j\right)$ cooperatively, i.e., so as to maximize the countries' joint welfare $SW_1 + SW_2$. The results of this numerical exercise presented in Table 4, confirm, once again, that the Nash equilibrium emission taxes are lower to the corresponding cooperative ones, i.e., $t_1^N < t_1^C$ and $t_2^N < t_2^C$.

[26] In an online Appendix we provide figures depicting these results when varying the cost of extraction of the resource ($\gamma$) given a low and a higher value of $c$.

[27] These results fail to hold if countries are not equally efficient in public sector pollution abatement. The numerical calibrations for this case can be provided upon request.

## 5 Regime *III*: Public Pollution Abatement Versus *ERS*

In this setting we continue to assume that country 1 imposes an emissions tax to control production-generated pollution, and that it uses the emission tax revenue to finance public pollution abatement. Country 2 adopts an *ERS*. The level of overall net pollution in each country is given by Eq. (17). Again, we consider a two-stage pre-commitment game. In the first stage, in order to maximize welfare, country 1 chooses non-cooperatively its emission tax ($t_1$), and country 2 sets non-cooperatively the *ERS* ($s_2$). In the second stage, the two firms, taking the governments' policy choices as given, choose their profit maximizing output quantities $q_1$, $q_2$ and the levels of resource use and of pollution abatement. The subgame perfect Nash equilibrium of the game is solved by backward induction.

### 5.1 Output Competition, Resource Use, and Private Pollution Abatement

Firm 1's profit maximization problem is given by Eq. (18 ) in *Regime II*, and its reaction function for $q_1$ is given by Eq. (22a). Similarly, firm 2 's profit maximization problem is given by Eq. (3) as presented in *Regime I* which yields the reaction function of firm 2 for $q_2$ given by Eq. (7b).

Solving simultaneously, we obtain equilibrium outputs for the two firms as functions of country 1's environmental tax ($t_1$), and country 2's emissions standard ($s_2$):[28]

$$q_1 = \frac{B(1+k+\gamma) - ks_2 - (2+k+\gamma)t_1}{k(2+\gamma) + (1+\gamma)(3+\gamma)},\ q_2 = \frac{B(1+\gamma) + (2+\gamma)ks_2 + t_1}{k(2+\gamma) + (1+\gamma)(3+\gamma)}, \tag{27}$$

where $\frac{\partial q_1}{\partial t_1} < 0$, $\frac{\partial q_2}{\partial s_2} > 0$, and $\frac{\partial q_2}{\partial t_1} > 0$. The corresponding levels of resource use by the two firms are $R_i = q_i/A, i = 1, 2$.

In maximizing profits, both firms choose the levels of pollution abatement given by Eqs. (18) and (3). Solving, the profits maximizing levels of $r_1$ and $r_2$ are:

$$r_1 = \frac{t_1}{k} \quad \text{and} \quad r_2 = \frac{B(1+\gamma) - (1+\gamma)(3+\gamma)s_2 + t_1}{k(2+\gamma) + (1+\gamma)(3+\gamma)}, \tag{28}$$

where $\frac{\partial r_i}{\partial t_1} > 0$, $i = 1, 2$ and $\frac{\partial r_2}{\partial s_2} < 0$. That is, (i) an increase in the environmental tax by country 1 motivates both firms to invest more in own pollution abatement, and (ii) the adoption of a stricter environmental standard by country 2 encourages the local firm to expand its own pollution abatement activity.

### 5.2 Nash Equilibrium: Emission Tax and *ERS*

In the first stage, each government chooses non-cooperatively its welfare maximizing environmental policy instrument, accounting for firms' reaction to their policy choice. The social planners' objective is to maximize their representative households' welfare, by choosing the optimal rates of environmental taxes, $t_1$ and $s_2$, respectively. Social welfare

[28] In order to ensure that $q_1 > 0$ and $q_2 > 0$, the conditions $t_1 < \frac{B(1+k+\gamma)-ks_2}{2+k+\gamma}$ and $s_2 > \frac{-B(1+\gamma)-t_1}{2(k+\gamma)}$ must hold. Since$k > 0$ and $\gamma > 0$, the second-order conditions for the maximization problems i.e. $\frac{\partial^2\pi_1}{\partial q_1^2} = -(2+\gamma) < 0$ and $\frac{\partial^2\pi_2}{\partial q_2^2} = -(2+k+\gamma) < 0$ and the stability condition $\Delta = k(2+\gamma) + (1+\gamma)(3+\gamma) > 0$ are also satisfied.

in country's 1 is given by Eq. (25) with the government satisfying its budget constraint in Eq. (16). Country's 2 social welfare function is given by equation:

$$SW_2(q_1,q_2,r_1,r_2;t_1,s_2) = (B-q_2-q_1)q_2 - \frac{1}{2}kr_2^2 - \frac{1}{2}\gamma q_2^2 - \frac{1}{2}\theta[(q_1-r_1)+(q_2-r_2)-cg]^2 + \left(\overline{q_2}-q_2\right)^2. \tag{29}$$

Substituting $q_1$, $q_2$, $r_1$ and $r_2$, from Eqs. (27) and (28), we obtain the countries' Nash equilibrium levels of welfare as functions, among other parameters, of $t_1$ and $s_2$. The associated first-order conditions ($\partial SW_1/\partial t_1 = 0$ and $\partial SW_2/\partial s_2 = 0$) cannot be solved analytically. We resort to numerical simulations to obtain the Nash equilibrium values for the endogenous variables, particularly of two policy instruments $t_1$ and $s_2$, given plausible values for the parameters of the model. The results are summarized in Table 2, and are discussed in the section to follow.

### 5.3 Main Results and Numerical Simulations

*Columns D* and *E* of Tables 2 and 3 report the results of the numerical simulations relevant to Regime III. Tables 2 and 3 are designed for a low and a high extraction cost respectively. Column *D* reports the Nash equilibrium values of the variables of the model for low values of the parameter *c*, implying a relatively inefficient public sector in abating pollution emissions. Column *E* reports the corresponding Nash equilibrium values for high values of *c*, implying a relatively efficient public sector in abating pollution emissions.[29] The following Proposition summarizes the results of the numerical simulations discussed in this section.

**Proposition 2** *Consider an international duopoly where production generates transboundary pollution. To regulate pollution emissions, country* 1 *imposes an emission tax with its proceeds financing the public sector's pollution abatement activity, and country* 2 *adopts an ERS. Based on the numerical simulations, the more efficient country* 1'*s public sector becomes in abating pollution, then, public pollution abatement vis-á-vis an ERS, leads to*:

**Result 5** (i) higher production and exports, thus, use of the depletable resource by firm 1 relative to firm 2, (ii) lower overall net production pollution ($Z$) in both countries relative to the level of net production pollution $\left(E_1\right)$ and $\left(E_2\right)$ generated, respectively, by the two firms locally.

**Result 6** lower welfare, independently of country 1's public sector's efficiency in abating pollution.

**Discussion** Result 5: The intuition of this result is as follows. The numerical calibrations indicate that the more efficient country 1's public sector becomes in abating pollution, then, (i) both countries adopt a laxer environmental policy. That is, country 1 reduces its emission tax and country 2 raises its environmentally related standard; (ii) the rate of decrease of the emissions tax is faster that the rate of increase in the *ERS*, i.e., $\left|\frac{dt_1}{t_1}\right| >$

[29] Again, a graphical illustration of these results for various parameter constellations is presented in an online Appendix.

$\left|\frac{ds_2}{s_2}\right| > 0$. Thus, firm 1's output and exports increase more that output and exports of firm 2, i.e., $\frac{dq_1}{q_1} > \frac{dq_2}{q_2} > 0$, thus, $\frac{dE_1}{E_1} > \frac{dE_2}{E_2} > 0$. However, since in both countries $Z$ falls, this is to say that the reduction in pollution due to public pollution abatement in country 1 outweighs the combined increase of net production pollution by the two firms, i.e., $E_1 + E_2$, due to their increased outputs.

*Result* 6: Per *Result* 5, the more effective the public sector is in abating pollution, a scheme of public pollution abatement is more effective in promoting exports and reducing overall net production pollution, while the *ERS* is more effective in preserving the natural resource from depletion. Since in our welfare specification, i.e., Eqs. (25) and (29), lends a high weight to the undepleted endowment of the resource, from which households derive utility, its impact in the numerical calibrations is dominant, rendering a higher welfare level to the *ERS* relative to public pollution abatement.[30]

A policy implication emerging from the analysis of this *Regime* is that choosing public pollution abatement as a measure of exports promotion, when (trade) policies of export subsidies are not available to implement, dominates the choice of an *ERS*. The latter instrument emerges as a more effective policy choice, under certain conditions, to public pollution abatement, in the pursuit of welfare and resource preservation considerations.

Following the analysis of previous regimes, numerical calibrations are performed assuming that country 1 chooses $\left(t_1\right)$ and country 2 chooses $\left(s_2\right)$ cooperatively, i.e., chosen so as to maximize their joint welfare, $SW_1 + SW_2$. The results of this numerical exercise presented in Table 4, confirm that the Nash equilibrium environmental policies are laxer than the corresponding cooperative ones, i.e., $t_1^N < t_1^C$ and $s_2^N > s_2^C$, where $t_1^C$ and $s_2^C$ are, respectively, the cooperative emission tax rate chosen by country 1, and the cooperative level of the *ERS* chosen by country 2.

## 6 Concluding Remarks and Policy Implications

Although there is a vast literature on trade and the environment that has already examined the effects of free trade on pollution, the opposite question has not been adequately addressed. The present study aims to answer whether "*clean environment can promote international trade*". To this end, we construct an international duopoly model to evaluate how different environmental policies affect trade flows, resource use, welfare levels, and pollution emissions. Our approach provides interesting new insights about the impact such policies can have on international trade and resource use, via exports competition among countries in world markets.

Our results indicate that, by and large, public pollution abatement emerges as a more effective exports promoting mechanism relative to emission tax-revenue recycling and to an *ERS*. Moreover, when a country's public sector is efficient in its pollution abatement activity and regardless of the private sector's level of abatement activity, overall net pollution falls both in the country pursuing this environmental policy, as wells as abroad. Revenue recycling, on the other hand, largely works as an export-contracting but resource preserving mechanism. It always encourages private pollution abatement, but its effect on emissions reduction is ambiguous. Environmentally related standards relative to public

[30] In our welfare specifications, the term capturing households' enjoyment from the undepleted endowment of the resource is quadratic, i.e., highly convex, with coefficient of one.

pollution abatement largely work as an export-contracting but resource preserving mechanism, but relative to revenue recycling work in the opposite way. However, environmentally related standards are always welfare-enhancing when compared to the other two policy regimes.

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