On the Strategic Effect of International Permits Trading on Local Pollution

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Abstract

We introduce a model of strategic environmental policy where two firms compete à la Cournot in a third market in the presence of multiple pollutants. Two types of pollutants are introduced: a local and a transboundary one. The regulator can only control local pollution as transboundary pollution is regulated internationally. We illustrate that when transboundary pollution is regulated through the use of tradable emission permits instead of non-tradable ones then a new strategic effect appears which has not been identified thus far. In this case, local pollution increases further. We caution that linking permit markets across regions may be welfare detrimental. We also provide evidence from the implementation of EU ETS over the pollution of particulate matters (PM_{10} and $PM_{2.5}$).

Keywords Environmental regulation · Multiple pollutants · (Non) tradable permits · Strategic interactions

JEL Classification F12 · F18 · Q58

1 Introduction

At the Paris climate conference (COP21) in December 2015, for the first time 195 countries celebrated a universal, global climate agreement. The implementation of the agreement remains, however, a challenge in a mutable political environment. Policymakers fear a loss in competitiveness as many firms are sensitive to environmental regulations and thus remain footloose. Indeed, several countries have been implementing carbon policies since the 1990s, although at the same time they have granted various forms of rebates to energy-intensive firms, e.g., free allocation of permits (Martin et al. 2014).

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Common practice suggests that cap and trade systems have been established to tackle CO₂ emissions within or across regions (see ICAP 2016; Schmalensee and Stavins 2017). For example, in 2017 two new schemes were launched in China and Ontario. The Chinese pilot system is linked to a national Emission Trading System (ETS). In a similar vein, Ontario's permit trading scheme is linked to the corresponding joint market of Quebec and California (ICAP 2016). In total, the ETSs cover almost a quarter of global emissions. This is expected to grow and benefit the participants (Doda et al. 2018). The most well-known cap and trade system, however, is the EU Emission Trading System (EU ETS) for CO₂ emissions which covers more than 11,000 power stations and manufacturing plants in the 28 EU member states as well as Iceland, Liechtenstein, and Norway (COM 2016). Similarly to CO₂ regulation, the governments tend to establish agreements for the local pollutants. An example is the 1999 Gothenburg protocol that defines national emission ceilings for a number of pollutants and came into force on May 17, 2005 (United Nations 1999). Interestingly, a severe form of local pollution that adversely affects human health—particulate matters (both PM_{10} and $PM_{2.5}$)—was not included in the initial amendments.¹ An interesting feature is that such agreements are signed separately and the regulation of each pollutant is decided independently (see IPCC 2014). In reality, CO₂ emissions co-exist with other pollutants, making the decision regarding the optimal level of pollution a difficult task.

Our contribution We aim to bring to light a new argument which casts doubt on the superiority of cap and trade schemes in the presence of multiple pollutants. We show that regional regulators face a strategic motive to set a more lenient standard for local pollution so as to promote the exporting activity of polluting firms provided that the regulation of the global pollutant conforms to the binding limits set in the agreement. The magnitude of this incentive depends crucially on the mode of regulation implemented for the transboundary pollutant. In particular, we argue that when transboundary pollution is regulated through tradable permits (or equivalently tradable emission standards) the regulator faces a stronger incentive to relax regulation for the local pollutant compared to the case where transboundary pollution is controlled through emission standards (or equivalently non-tradable permits). The rationale is as follows. A laxer policy for the local pollutant implies lower abatement (compliance) costs for the firms and higher production. This in turn results in higher emissions for the other pollutant. When this pollutant is regulated through tradable permits the firms can still increase their production by purchasing emission permits. On the other hand, when the transboundary pollutant is regulated through emission standards the firms do not have this flexibility. This result implies that linking regional permit markets to a larger market may be welfare detrimental as the regional regulators tend to overlook local pollution.

Our two alternative scenarios for regulating the transboundary pollutant are consistent with our leading EU example with the two alternative regulatory schemes, before and after the introduction of tradable permits in 2005. To support our theoretical findings we focus on several export sectors in the EU 28 countries that participate in the EU ETS launched in 2005. We illustrate that local pollution as expressed by concentrations of two categories of particulate matters, i.e., $PM_{2.5}$ and PM_{10} , increased after the introduction of the EU ETS in the exporting sectors that participate in the permits market, while in both non-exporting sectors and exporting sectors that are not participating in the EU ETS, the corresponding

¹ The World Health Organization urges the development of more effective strategies in dealing with particulate matters and provides evidence of the severe effects on human health (WHO 2013).

concentrations have decreased over time. We further use a difference-in-differences analysis which is consistent with our theoretical predictions.

Our theoretical findings and also the evidence from the European experience question the effectiveness of permits trading when local pollution is also present. This can be an instructive example for the introduction of the new tradable permits scheme in China where the $PM_{2.5}$ and PM_{10} very often exceed the emergency threshold levels, provided that the central government now encourages the regional regulators to also control for local pollution (see Zheng et al. 2014). This urgent need to regulate local pollution is also confirmed by a recent study published in *Nature* (Zhang et al. 2017) which points out the negative health impacts of $PM_{2.5}$ pollution associated with international trade. More specifically, the authors have assessed the global health impacts related to international trade and have found that, of the 3.45 million premature deaths associated with the $PM_{2.5}$ in 2017 worldwide, about 22 percent were linked to goods and services produced in one region and consumed in another. This clearly highlights the contribution of the export-oriented sectors to local pollution in countries such as China which are suffering from high levels of fine particulate matter pollution.

Organization of the paper In Sect. 2 we present the related literature. Section 3 illustrates the theoretical model. Then, in Sect. 4 the comparative statics of the model, the welfare analysis, and the role of spillovers are presented and, in Sect. 5, the discussion of several extensions follows. In Sect. 6 an application of the EU ETS is presented to support and estimate our theoretical findings. Finally, Sect. 7 concludes. The main formal proofs for Sect. 4 are collected in “Appendix 1”, while the proofs for Sect. 5 are presented in “Appendix 2”.

2 Related Literature

The environmental policy as a means to affect the competitiveness of the regulated sectors has been studied in the ‘Strategic Environmental Policy’ or ‘Ecological Dumping’ literature, established, among others, by Conrad (1993), Barrett (1994), Kennedy (1994), Rauscher (1994), and Neary (2006). In particular, Conrad (1993), Kennedy (1994), Barrett (1994), and Neary (2006) argue that the level of regulation, regardless of the type of the pollutant or the mode of regulation, is set inefficiently low.² All these studies conclude that the presence of a strategic incentive is detrimental for welfare.³ Nannerup (2001) and Eichner and Pethig (2009) argue that even if regulation regarding CO_2 is restricted by international agreements, the governments may discriminate against environmental policies favoring the exporting against the non-exporting sectors. A parallel literature focuses on strategic motives under trade liberalization. Burguet and Sempere (2003) illustrate that the strategic incentive is dampened when the two trading countries mutually reduce their tariffs and, most importantly, that welfare may increase. Baksi (2014) extends his analysis, allowing for transboundary pollution which creates a bias in favor of regional agreements

² Ulph and Valentini (2001) argue that the magnitude of the strategic incentives is adversely affected when the firms can relocate, while Kayalica and Lahiri (2005) point out that it also depends on the firms’ country of origin. Ulph (1996) and Nannerup (1998) extend the ecological dumping models by introducing R&D choices and imperfect information. In contrast, Greaker (2003) shows that tight environmental policy may be optimal if the environment is an inferior input.

³ Fredriksson and Millimet (2002) attest this strategic interaction.

versus multilateral ones. Lapan and Sikdar (2019) find that internationally tradable permits lead to higher pollution compared to non-tradable permits in the case where there is intra-industry trade in goods along with trade in emissions permits and countries strategically choose environmental policies.

Antoniou et al. (2014) show that this race to the bottom may even be reversed if the two exporting countries are linked through a permits market. Interestingly, Boadway et al. (2013) show that creating a permits market for transboundary pollution may lead under certain conditions to the efficient solution even if the regions act unilaterally. Tsakiris et al. (2017) in a perfectly competitive trade model with capital mobility and transboundary pollution also argue that linking tradable permit markets may be beneficial. All these studies share the common feature that the introduction of tradable permits can be welfare-enhancing.

Although very informative, these models assume that only a single pollutant exists: local or transboundary. Our study extends the original models of the strategic environmental policy literature by allowing for an additional pollutant. The interaction between the different components of the abatement cost function is critical. Interestingly, we show that the policy mixture affects the magnitude of the strategic incentives, whereas in the aforementioned studies no discrimination in terms of results regarding the mode of regulation has been identified. We argue that in a multiple pollutants framework, contrary to the single pollutant models, the introduction of tradable permits across countries or regions may be welfare detrimental.

The linkages arising in the presence of multiple pollutants, especially from a theoretical standpoint, have been underinvestigated. Potential synergies are often captured in studies as ‘ancillary’ benefits from the reduction of other pollutants (e.g., Burtraw et al. 2003; Groosman et al. (2011); and Finus and Rübbelke 2013).⁴ Ambec and Coria (2013) analyze a mix of tax and permit policies under uncertainty and determine the optimal policy depending on the substitutability or complementarity of pollutants. Montero (2001), Caplan and Silva (2005), Fullerton and Karney (2018), Stranlund and Son (2019), and Ambec and Coria (2018) in different contexts to ours, also stress that the implementation of different policy instruments may yield different outcomes, and highlight the necessity of joint regulation. More specifically, Ambec and Coria (2018) argue that efforts to reduce greenhouse-gas emissions do not necessarily lead to a reduction of local pollutants. Moreover, measures that improve local air quality do not always cut carbon emissions. This points out the importance of the right choice of policy instrument if unintended consequences are to be avoided. Montero (2001) focuses on the tradable permits markets of the various pollutants under the presence of imperfect information and incomplete enforcement and provides the conditions under which these markets should be integrated or separated. Stranlund and Son (2019), also under imperfect information, set exogenously the level of the co-pollutant and then argue that when this pollutant is regulated through tradable permits, the policy choice of the primary pollutant does not depend on the mode of regulation. Caplan and Silva (2005) show that the use of permits both for a global and a local pollutant may lead to a Pareto superior welfare outcome. It is necessary, however, to establish a distributional mechanism for the allocation of permits which is equivalent to transfers. This feature is shared by Ambec and Coria (2018) when the global pollutant is regulated through a tax and revenues are lump sum redistributed to the local communities. Moslener and Requate (2007) derive the optimal abatement strategies in a dynamic multi-pollutant model.

⁴ The interested reader may find several examples of substitutability or complementarity of pollutants in studies by Greenstone (2003), Gamper-Rabindran (2006), Ren et al. (2011), Holland (2012), and Agee et al. (2014).

An interesting feature identified in our study, which is missing from the existing theoretical papers, is the correlation of the abatement costs of different pollutants not only through the presence of synergies but also through an indirect channel; that is, the regulation of one pollutant affects output and this directly affects the abatement costs of the other pollutant. Holland (2012) in a different model also defines an output effect, which is unrelated to ours. Holland (2012) introduces pollution as an input and the output effect follows from the changes in the corresponding price of pollution. In contrast, we model pollution as a public bad. Ren et al. (2011) study in a general equilibrium model two environmental externalities generated by the production of two different goods that are substitutes in the market. They show that the two taxes used to control the two externalities interact and jointly affect the level of emissions of both externalities. Also, the elasticity of substitution between the two goods affects the level of the second-best taxes. The linkage through output markets is created through the demand, whereas in our study output interacts within the different components of the abatement cost function. Therefore, our results provide a new linkage between pollutants for future investigation.

3 The Model

Summary In the baseline scenario we have a symmetric two-country, two-stage game. Each country is represented by a government and a firm. Both firms compete and sell their production exclusively on the global market, engaging in Cournot competition. They emit two pollutants—one local and the other global—as by-products of output. The latter is regulated through an international emissions system (non-tradable (NT) or tradable (T) permits) which is exogenous to the game. The local pollutant is regulated through local emissions limits. In *stage 1* of the game the governments simultaneously set the emissions limits for the local pollutant, and in *stage 2* the firms decide on the production and emissions of the global pollutant when possible. Both governments face a strategic incentive to weaken the regulation of the local pollutant in order to help the domestic firm capture a larger share of the global market for the product, hence making larger profits. The emissions of the global pollutant emitted by the exporters tend to increase, and the firms aim to buy permits on the global market if possible. If not, the firms must increase their abatement which, in turn, leads to higher abatement costs. Hence, the strategic motives of the government (to soften regulation of the local pollutant) are weakened.

The domestic firm's problem

We start by setting up the domestic firm's problem, i.e., stage 2 of the game.⁵ Consider a domestic firm with production (output) x where production costs are normalized to zero. The firm faces binding emission caps, $\bar{e}_1$ and $\bar{e}_2$, on the local and global pollutants respectively that are emitted as by-products of output. In the tradable permits scenario the firm can also sell (purchase) emissions $e_2 > 0$ (< 0) for the global pollutant at a price P^e . Each firm has a private abatement technology (a_i) for each pollutant $i = 1, 2$, which allows adherence to the binding level of regulation set by the governments given by

⁵ Since the two firms (countries) are assumed to be symmetric, we only present the explicit variables and functions of the home firm (country). All variables regarding the foreign firm and country are denoted by capital letters.

$$a_i = \theta_i x - \bar{e}_i + (e_i), \quad (1)$$

where $\theta_i > 0$ is a pollution intensity coefficient. Abatement costs are

$$c(a_1, a_2) = c_1(a_1) + c_2(a_2) + \gamma a_1 a_2, \quad (2)$$

so if the parameter $\gamma \neq 0$ there is some interaction between the abatement efforts, with the negative (positive) γ implying that the abatement efforts on one pollutant complement (substitute) the abatement efforts on the other. Following the relevant literature (e.g., Barrett 1994) we assume that the abatement cost is increasing and convex. That is, the Hessian matrix $\mathbf{H}$ must be positive definite.⁶ When this holds, a tightening in environmental policy implies higher marginal abatement costs (see equation (1)). In what follows, we focus on $\gamma = 0$, and we explore the role of spillovers ($\gamma \neq 0$) in Sect. 4.

The firm's profits are simply revenues, $r(x, X)$, minus abatement costs, $c(a_1, a_2)$, plus (minus) any potential revenues (expenses) from selling (buying) a number of permits, $P^e e_2$, i.e.,

$$\pi(x, X, a_1, a_2) = r(x, X) - c(a_1, a_2) + P^e e_2.$$

Note that revenues are a function of x but they are also of the foreign country's production (X) and the two products are substitutes, i.e., $r_X < 0$. In the main part of the model we assume that the permits price P^e is fixed at a specific level as the firms participate in a thick permits market.⁷

The domestic government's problem The domestic government sets an emissions cap for the local pollutant, $\bar{e}_1$, to maximize domestic welfare, which is firm profits minus the damages from pollution, denoted by $d(\bar{e}_1, \bar{e}_2 + \bar{E}_2)$.⁸ The damage is increasing and convex with respect to pollution. Since there is no consumption of the good in the two countries, welfare depends solely on profits and on the damage function. Denoting domestic welfare by w we have

$$w(x, X, a_1, a_2, \bar{e}_1, \bar{e}_2 + \bar{E}_2) = \pi(x, X, a_1, a_2) - d(\bar{e}_1, \bar{e}_2 + \bar{E}_2). \quad (3)$$

Solution of the model We solve the problem by backwards induction and the equilibrium concept is subgame perfect Nash equilibrium. At stage 2, each firm maximizes its profits with respect to output, the corresponding abatement levels, and the number of permits (if allowed) it is willing to trade:

$$\max_{x, a_i, e_2} \pi \text{ s.t. (1)} \iff \max_{x, e_2} \pi$$

The first-order conditions for the two firms in the two scenarios, (NT) and (T), are:

⁶ When a variable appears as a subindex of a function it denotes a partial derivative. In the case where more variables are indexed we refer to the corresponding higher order partial derivatives. Mathematically the convexity assumption translates to $c_{a_i}(a_i) > 0$, $c_{a_i a_i}(a_i) > 0$ and $c_{a_i a_1}(a_1) c_{a_2 a_2}(a_2) - \gamma^2 > 0$. When this holds the costs are also convex with respect to output, i.e., $c_{xx}(a_1, a_2) > 0$.

⁷ In Sect. 5.4 we allow for an endogenous permits price and show that our main implications remain unchanged. Moreover, in Sect. 5.5 we analyze the effects of changes in the permits price.

⁸ Throughout the analysis, pollution emitted from any other sectors is captured by a fixed term in the damage function. To make the two scenarios comparable we assume that in both cases the exogenously given number of emissions for the global pollutant is equal.

$$\left. \begin{aligned} \pi_x &= r_x(\cdot) - c_x(\cdot) = 0 \\ \Pi_X &= R_X(\cdot) - C_X(\cdot) = 0 \\ \pi_{e_2} &= P^e - c_{e_2}(\cdot) = 0 \\ \Pi_{E_2} &= P^e - \bar{C}_{E_2}(\cdot) = 0 \end{aligned} \right\} \begin{matrix} (NT) \\ (T) \end{matrix} \quad (4)$$

The second-order conditions for the home are always satisfied when $\pi_{xx} < 0$, $\pi_{e_2e_2} < 0$, $\delta^H \equiv \pi_{xx}\pi_{e_2e_2} - \pi_{xe_2}^2 > 0$, while similar conditions follow for the foreign. Moreover, $\pi_{xX} < 0$ ensures that the output reaction function is downward sloping and that outputs are strategic substitutes.

Given that the firm responds optimally (in the second stage of the game) to the domestic government's choice of regulation then x , a_1 and a_2 are all functions of $\bar{e}_1$. However, the domestic regulator must also take into account the effect of her choice on foreign production and how it affects domestic profits. The regulator's first-order condition in stage 1 is

$$\left(\frac{dw}{d\bar{e}_1} \right)^n = \underbrace{\left(\frac{\partial \pi^*}{\partial x^*} \frac{\partial x^*}{\partial \bar{e}_1} + \frac{\partial \pi^*}{\partial e_2^*} \frac{\partial e_2^*}{\partial \bar{e}_1} \right)}_{=0 \text{ (FOCs)}} + \underbrace{\frac{\partial \pi^*}{\partial \bar{e}_1}}_{\text{abatement effect (MC)}} + \underbrace{\frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \bar{e}_1}}_{\text{strategic effect}} - \underbrace{\frac{\partial d}{\partial \bar{e}_1}}_{\text{regulation benefit (MD)}} = 0, \quad (5)$$

where $n = NT$, T and star denotes stage 2 equilibrium values.⁹ We assume that the welfare function is twice differentiable and that the Hessian matrix of the second order partial derivatives (for home and foreign) is negative definite. This implies that the second-order conditions are satisfied and that (local) pollution in home and foreign are strategic substitutes which translates to negatively sloped reaction functions. To restrict our attention to economically interesting cases we assume that when the foreign country opts for zero local emissions, i.e., $E_1 = 0$, then it is optimal for the domestic country to choose a strictly positive level of emissions, i.e., $\arg \max_{\bar{e}_1} w := \bar{e}_1^o > 0$.

Applying the envelope theorem, the terms in parenthesis are equal to zero. The second term on the RHS corresponds to the decrease in abatement costs when regulation is relaxed, while the next one indicates how the strategic effect influences foreign output and how this, in turn, affects profits. The last term denotes the marginal benefits from regulation.

4 Main Results

4.1 Comparative Statics

The comparative statics analysis focuses on the sign of the so-called 'strategic effect' that appears in eco-dumping models. The strategic effect can be described as the effect that home's environmental regulation has on the foreign firm's stage 2 equilibrium output, i.e.,

⁹ The aggregate levels of the global pollutant are already determined at a prior stage and are independent of the mode of regulation. Indeed, on average the CO₂ emissions in the EU 27 countries, excluding Romania, Bulgaria, and Malta, increased by 1.9% between 2005 and 2007 (COM 2008).

$\frac{\partial X^*}{\partial \bar{e}_1}$ or $\frac{\partial X^*}{\partial \bar{e}_2}$. In models of standard strategic environmental policy, with a single pollutant the sign of each derivative separately is negative.

Since the regulators in the two countries are restricted by an international agreement regarding transboundary pollution they only have a limited degree of freedom which translates to a unique choice variable, that is, $\bar{e}_1$ and $\bar{E}_1$ respectively. The first necessary step toward our results is to determine the sign of the strategic effect $\frac{\partial X^*}{\partial \bar{e}_1}$ in the two different scenarios and compare its magnitude. The following proposition summarizes this:

Proposition 1 (a) Under both scenarios $\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^n < 0$, $n = NT, T$. (b) The strategic effect is stronger in the tradable permits scenario, $\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} > \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T$.

The results of Proposition 1a reproduce the major results of the strategic environmental policy literature of a single pollutant and extend it to a multiple pollutants set-up. Irrespective of the scenario under study when the level of transboundary pollution is fixed (e.g., because of an international agreement), there is an incentive to relax the regulation of the local pollutant. In the following, we explain the mechanism in the two scenarios.

Non-tradable permits: In this case the marginal abatement costs from (2), $c(a_1, a_2) = c_1(a_1) + c_2(a_2)$, for the local and the global pollutants are $c_{a_1} = c_{1a_1}(a_1)$ and $c_{a_2} = c_{2a_2}(a_2)$ respectively. Relaxing regulation of the local pollutant, i.e., increasing $\bar{e}_1$, decreases abatement (for the local pollutant) as described by equation (1), i.e., $\frac{\partial a_1}{\partial \bar{e}_1} = -1$. As a result, local marginal abatement costs also decrease, i.e., $c_{1a_1}(a_1) \frac{\partial a_1}{\partial \bar{e}_1} < 0$. The decrease in marginal costs fashions an incentive to the domestic firm to increase its output, x . Yet higher output creates an upward shift of the abatement requirements for the global pollutant, i.e., $\frac{\partial a_2}{\partial x} = \theta_2 > 0$. Following this, the firm abates more in order to conform with the binding level of emissions for the global pollutant. Hence, the effect over the corresponding marginal abatement costs is positive, $c_{2a_2}(a_2) \frac{\partial a_2}{\partial x} > 0$. The latter reduces the effectiveness of the initial change of local pollution on production. Put differently, this new channel creates a potential negative *feedback effect* which, when realized, is not sufficient to reverse the direct effect on production described above. Yet higher domestic production implies lower foreign production through the reaction function of output, $\frac{\partial X}{\partial x} < 0$, which is described by the strategic effect. Indeed, under the *NT* scenario the *feedback effect* is present and implies that in the single pollutant case, where the global pollutant is non-existent, the strategic effect in absolute value will be larger.

Tradable permits: Again, relaxing the local standard, $\bar{e}_1$, decreases the marginal abatement cost, $c_{1a_1}(a_1) \frac{\partial a_1}{\partial \bar{e}_1} < 0$, and the firm tends to increase its production. Yet higher production implies higher abatement requirements for the second pollutant, which tend to increase the corresponding costs, $c_{2a_2}(a_2) \frac{\partial a_2}{\partial x} > 0$. Contrary to the *NT* scenario, the firm can now purchase permits at a fixed price and thus $c_{2e_2}(a_2) = c_{2a_2}(a_2) \frac{\partial a_2}{\partial e_2} = P^e$ from (4). The marginal abatement costs of the global pollutant are fixed and the *feedback effect* disappears.

Comparison of the strategic effects: In Proposition 1b we compare the strategic effects in the two alternative scenarios after introducing multiple pollutants, i.e., $\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT}$ and $\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T$. This comparison is critical for the welfare analysis to follow next. As a benchmark, in order to level the playing field between the two schemes under study and allow for

a general comparison we set the level of regulation for the local and the global pollutant, before any change is taken into consideration, to be the same across the two scenarios. At this initial point there is no need for permit trading in the T scenario and the abatement costs are the same. This is, however, redundant when we allow for (the commonly used in the literature) linear demand and marginal abatement cost functions as we will show next.

Proposition 1b implies that if the government in the home country relaxes the emissions standard of the local pollutant then the reduction in the foreign firm's output is greater when the global pollutant is regulated through a permits market rather than an emissions standard. The rationale for this result follows because of the presence of the *feedback effect* under the NT scenario. On the contrary, under the T scenario, the *feedback effect* disappears as, instead of abating the extra emissions associated with the output increase, the firms purchase allowances in the permits market at a fixed price. To better understand the difference across the two scenarios we present an extreme case where the slope of the marginal abatement cost for the transboundary pollutant ($c_{2a_2a_2}$) is infinite. Then, under the NT scenario, relaxing the local emission standard cannot increase output as it must adhere to the binding level of transboundary emissions and the strategic effect tends to zero. When, however, tradable permits are in place the strategic effect remains negative as the firm may resort to the permits market to support higher levels of output.

4.2 Welfare Effects

In the original eco-dumping literature the presence of the strategic effect in both exporting countries is detrimental for welfare. Both countries are involved in a situation where both exporters produce too much output and emit too much pollution. Therefore, we shall expect that the higher this effect is in absolute terms, the higher the welfare losses.

To set this formally we study the welfare-maximization problem of the regulator in the home country (5). In a context where the regulator uses environmental policy only to deal with the externality, i.e., non-strategically (NS), the first-order condition is reduced to the simple rule that the marginal cost of abatement should be equal to the level of the marginal damage, $\left(\frac{\partial \pi^*}{\partial \bar{e}_1}\right)^{NS} = \left(\frac{\partial d}{\partial \bar{e}_1}\right)^{NS}$. When, however, the regulator acts strategically (S), a bias in favor of laxer regulation appears due to the strategic effect which implies $\frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \bar{e}_1} > 0$ in (5). As a result, a government has an incentive to increase local pollution for trade purposes, i.e., $(\bar{e}_1)^S > (\bar{e}_1)^{NS}$ (see Ulph 1996).

Given the equality of pollution levels across the two scenarios when the governments act non-strategically (benchmark) and Proposition 1b the following proposition compares the two scenarios in terms of pollution in equilibrium:

Proposition 2 *The resulting equilibrium level of local pollution under tradable permits is higher than the corresponding one under non-tradable permits, i.e., $(\bar{e}_1^*)^T > (\bar{e}_1^*)^{NT}$.*

Proposition 2 derives immediately from Proposition 1b and the first-order condition for welfare-maximization in (5). It states that the presence of a permits market for the global pollutant leads to higher local pollution as a result of laxer regulation compared to the case where the global pollutant is controlled directly through an emissions standard. The strategic effect, $\frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \bar{e}_1}$, differentiates the two scenarios when departing from the non-strategic

Fig. 1 Aggregate welfare levels under tradable and non-tradable permits

equilibrium (*NS*) where these two are equivalent in terms of pollution. The strategic effect has a larger impact on profits when tradable permits are in place, which in turn strengthens the incentive for relaxing the standard for local pollution. Naturally, equilibrium outputs will be higher.

To facilitate the welfare analysis we introduce Fig. 1 where the joint welfare levels, i.e., $(w^j)^n \equiv (w + W)^n$, $n = T, NT$, are represented for each scenario as a concave function of aggregate local pollution. Given symmetry, in equilibrium the welfare levels in the two countries are equalized and it holds $(w^*)^n = (W^*)^n = \frac{1}{2}(w^{j*})^n$. The following proposition provides a welfare ranking across the two alternative policy scenarios:

Proposition 3 *The resulting equilibrium welfare under tradable permits is lower than the corresponding one under non-tradable permits, i.e., $(w^*)^T < (w^*)^{NT}$.*

When transboundary pollution is regulated through the use of tradable permits we end up with welfare losses compared to the case where each country directly regulates pollution through emission caps.

Moving to the right of the point of intersection which corresponds to the non-strategic regulation level (benchmark), where the two scenarios are by construction equivalent, our results show that for any given level of pollution non-tradable permits imply higher aggregate welfare compared to the tradable permits case. The key feature is to illustrate that at the non-strategic node the slope of the joint welfare function is larger in absolute

terms in the tradable permits case compared to the non-tradable permits one. Intuitively, this follows from the different magnitudes of the strategic effects across the two scenarios. The unilateral incentive to relax regulation in order to increase the profits of the domestic firms leads to a race to the bottom where too low profits and too much pollution are obtained in equilibrium, which implies, in turn, lower welfare levels. Naturally, when this strategic motive is stronger the race to the bottom is exacerbated. Our contribution is linked to the latter observation since when permits are allowed (scenario *T*) the strategic incentive to relax regulation is sharpened, which leads to lower welfare levels.

It is important to stress here that in the tradable permits scenario a permit revenue (expenses) effect shall be included in (5) through the change in the permits price, i.e., $\frac{\partial P^e e_1^s}{\partial \bar{e}_1} < 0$. This effect is generally negative as a higher local emissions cap increases both production and the demand for permits. This in turn raises the permits price and the overall effect is negative because the firm is a permit buyer. As we argue in Sect. 5.4, this effect is expected to be rather small as the market for permits involves many sectors of the economy with numerous firms, whereas it is caused by the increase in the permits demand of a single firm. In addition, at the point of intersection in Fig. 1 no permits trading takes place and thus the effect converges to zero.¹⁰

Another feature which deserves some qualification is that the joint welfare maxima in the two scenarios differ (see Fig. 1). This holds because the costs are different between the two scenarios. To better understand the rationale we focus on the amount of local emissions, $(\bar{e}_1 + \bar{E}_1)^{NT}$, that maximizes the joint welfare in the non-tradable permits scenario. Under tradable permits the firms face an additional option to sell permits which benefits the firms, otherwise they would not have engaged in permit trading in the first place. Removing the permit revenues (expenses) from the welfare function (3) does not restore the equivalence of joint welfare optima across the two scenarios. Instead, the regulator faces an additional motive to increase local emissions, which in turn leads to permit purchases or lower sales.

4.3 The Role of Spillovers

Here we will show that the spillovers influence the magnitude of the strategic effect, and under certain conditions can even reverse its sign in the non-tradable permits case. When the regulator alters its local standard this affects the marginal abatement costs of the local and the global pollutant $c_{a_1}(a_1, a_2) = c_{1a_1}(a_1) + \gamma a_2$ and $c_{a_2}(a_1, a_2) = c_{2a_2}(a_2) + \gamma a_1$ respectively. A change in local pollution influences the marginal abatement cost of the local pollutant through $c_{1a_1}(a_1)$, and the marginal abatement cost of the global pollutant through γa_1 . When non-tradable permits are in place (*NT*) and the pollutants are complements ($\gamma < 0$) then abating one pollutant decreases the marginal cost of abating the other. This reduces the effectiveness of a laxer standard over the marginal production costs and thus the strategic effect is less severe. When the pollutants are substitutes ($\gamma > 0$) the opposite holds and the effect of a laxer local standard may be magnified.

¹⁰ In reality, this effect can never alter the incentives of the regulator so as to strengthen the local standard. To understand this let us consider that this indeed happens. Then, a stronger local standard (from our intersection point) will lead the firm to sell permits, the price will fall and this effect will turn positive, which is apparently a contradiction.

Table 1 $c_{1a_1a_1} > c_{2a_2a_2}$

γ	$-\infty$	$-\gamma_2$	0	γ_2	$+\infty$
<i>NT</i>	<i>ND</i>	–	–	<i>ND</i>	
<i>T</i>	<i>ND</i>	–	–	<i>ND</i>	

Table 2 $c_{1a_1a_1} < c_{2a_2a_2}$

γ	$-\infty$	$-\gamma_2$	$-\gamma_1$	0	γ_2	$+\infty$
<i>NT</i>	<i>ND</i>	+	–	–	<i>ND</i>	
<i>T</i>	<i>ND</i>	–	–	–	<i>ND</i>	

More specifically, in terms of our model when $\gamma = -\gamma_1 \equiv -\frac{\theta_1}{\theta_2}c_{1a_1a_1} < 0$ (see proof of Proposition 1), that is the pollutants are complements, the strategic effect is zero in the (*NT*) scenario. Thus, the incentive of the regulator to relax the local pollutant disappears as the lower marginal costs are then offset by the spillover effect. When the degree of complementarity exceeds this level the strategic effect turns positive. This is not possible under the standard eco-dumping models with a single pollutant (e.g., Barrett 1994) and it can also serve as an alternative argument for the Porter hypothesis.

In the tradable permits case the strategic effect can converge to zero under any type of spillovers, complements or substitutes. When $\gamma \in (-\gamma_2, \gamma_2)$, where $\gamma_2 \equiv \sqrt{c_{1a_1a_1}c_{2a_2a_2}}$, the strategic effect has a negative sign (see proof of Proposition 1). Note that γ cannot equal or exceed γ_2 in absolute terms as the assumption of convex costs is then violated. As γ departs from zero and follows a policy change the volume of permit trading adjusts such that the last two equations in (4) are satisfied. When the pollutants are substitutes, $\gamma > 0$, and following a more lenient standard for the local pollutant the component of the marginal abatement cost of the global pollutant that captures the spillovers, γa_1 , tends to decrease. Given that the permits price is fixed, the firm finds it profitable to sell permits. Then, the other component of the spillovers affecting the local marginal abatement costs, γa_2 , increases. Hence, the initial policy change intended to promote output is not effective as the firm prefers to act in the permits market. A similar argument also applies when the two pollutants are complements, with the difference that the firm will now purchase permits following an increase in the local standard.

To provide a clear comparison of the two scenarios under study we introduce Tables 1 and 2. Wherever we use *ND* it means that the assumption of convexity is not satisfied. In Table 1 we consider the case where $c_{1a_1a_1} > \gamma_2$ which holds true when $c_{1a_1a_1} > c_{2a_2a_2}$. In Table 2 we consider the opposite case, i.e., $c_{1a_1a_1} < c_{2a_2a_2}$.

From Table 1 we observe that the strategic effect is always negative. Yet, when γ converges to γ_2 in absolute values the strategic effect in *T* converges to zero. Within this range the strategic effect in *NT* is always negative. Therefore, under this specification the ordering of the strategic effects is reversed with respect to Proposition 1b for a relatively high degree of complementarity or substitutability. The rationale follows across the lines analyzed above. From Table 2 we infer that the reversal of the strategic effects across the two scenarios can occur only for a relatively high degree of substitutability. Again, the strategic effect in *T* converges to zero when γ approaches γ_2 , whereas the strategic effect under *NT* always remains negative when the pollutants are substitutes.

Our analysis shows that for intermediate values of γ , in both scenarios the strategic effect is negative regardless of the regulatory regime. Therefore, even if an agreement is reached regarding the transboundary pollutant, there is an incentive to disregard the local pollutant. Nonetheless, for higher degrees of spillovers this conclusion should be used with caution. The technology in place is critical and under the conditions analyzed above the introduction of tradable permits can mitigate the strategic incentives and lead to higher welfare levels compared to the non-tradable permits scenario. This is an interesting feature because tradable permits can be beneficial with high degree of spillovers not for cost efficiency reasons solely but also for strategic motives.

5 Extensions-Linear Specification

5.1 Stylized Main Model

We first introduce a linear specification of the model to verify the main result. In particular, we assume a linear inverse-demand function as $P = B - b(x + X)$ and a quadratic abatement cost function as $c(a_1, a_2) = \sum_{i=1}^2 \frac{1}{2} g_i a_i^2 + \gamma a_1 a_2$. Note that B is the demand intercept, $b > 0$ the slope of the inverse demand, and $g_i > 0$ the slope of the marginal abatement cost of the corresponding pollutant. For simplicity, we set the pollution intensity coefficients $\theta_i = 1$ while all the rest remain the same, as in the benchmark model.

Comparing the two strategic effects, we obtain the following remark:

Remark 1 There exists a $\gamma \in (\max\{-g_1, -g_2\}, \bar{\gamma})$ such that $\left(\frac{\partial X^*}{\partial e_1}\right)^{NT} > \left(\frac{\partial X^*}{\partial e_1}\right)^T$. If $\gamma \in (-g_1, -g_2)$ or $\gamma \in (\bar{\gamma}, \gamma_2)$ then $\left(\frac{\partial X^*}{\partial e_1}\right)^{NT} < \left(\frac{\partial X^*}{\partial e_1}\right)^T$.

Note that $\bar{\gamma} \in (0, \gamma_2)$ implies that the pollutants are substitutes and denotes a cut-off value where the strategic effects are equal across the two policy scenarios (see proof of Remark 1 in “Appendix 2”). Remark 1 states that for moderate values of γ the results presented in the general model are not altered. In particular, the difference in the strategic effects under tradable and non-tradable permits is negative as long as the degree of complementarity does not exceed in absolute terms the slope of any of the two direct marginal abatement costs. If, however, $g_1 > g_2$ then a higher degree of complementarity leads to a reversal of the ordering between the strategic effects for $\gamma < -g_2$. The reason is that in the non-tradable permits case the direct and the indirect effects move in the opposite direction and converge. When the two pollutants are mildly substitutes, the strategic effect in NT is larger than the one in T . The spillover effect tends to mitigate the difference between the two strategic effects because in the tradable permits case the firm reacts to the policy change by trading permits. This reduces the magnitude of the regulatory change effect on the aggregate marginal abatement costs. Following this argument, when the degree of substitutability takes relatively high values, i.e., $\gamma > \bar{\gamma}$ the ordering of the strategic effects is reversed. The intuition follows the one described in the general model.

5.2 Asymmetric Cases

Allowing for asymmetries in abatement cost functions or different preferences for environmental protection does not alter the results regarding the relative magnitude of the strategic effects qualitatively. To this end, we modify our linear example so that the foreign abatement cost function is now assumed to be $C(A_1, A_2) = \sum_{i=1}^2 \frac{1}{2} G_i A_i^2 + \gamma A_1 A_2$, where $G_i \neq g_i$ denotes the slope of the marginal abatement cost of each pollutant. To preserve clarity we set $\gamma = 0$. Regarding the asymmetries in environmental damage the analysis is trivial as any asymmetry in the damage functions does not influence the stage 2 equilibrium values which are determined by the firm decisions at that stage, thus leaving the strategic effect unaffected. Hence, the following result focuses solely on the case where the abatement costs are asymmetric. Under asymmetric abatement cost, we obtain the following remark:

Remark 2 $\left(\frac{\partial X^*}{\partial \bar{e}_1} \right)^{NT} > \left(\frac{\partial X^*}{\partial \bar{e}_1} \right)^T$.

This ordering of the strategic effects between our two scenarios remains unchanged and the intuition follows suit. When tradable permits are in place the second component of the abatement cost function is no longer binding and thus the firm can increase production following a laxer policy for the local pollutant.

5.3 Emission Taxes

The analysis regarding taxation on the global pollutant is straightforward and follows across the same lines as in the analysis of tradable permits. The presence of an emissions tax for the global pollutant fixes the marginal abatement cost at this level independently of the changes in production following the changes in the regulation of the local pollutant. Put differently, setting a tax for the global pollutant is equivalent to allowing for tradable permits at a given price.

More interesting is the analysis regarding the regulation of the local pollutant through an emissions tax and it deserves further qualification. We define the emissions tax for the local pollutant in the domestic country as t_1 . The two scenarios that we compare are (1) tax, non-tradable permits, and (2) tax, tradable permits. The strategic effect is captured by the term $\frac{\partial X^*}{\partial t_1}$ and is positive, regardless of the scenario, as an increase in taxation implies higher marginal abatement costs and thus lower production for the domestic firm. Following this decrease in production the foreign firm increases its own production. We set $\gamma = 0$ to focus on the direct effects. Spillovers have similar effects as in the main model. The following remark presents the strategic effects and their relative magnitude.

Remark 3 $\left(\frac{\partial X^*}{\partial t_1} \right)^T > \left(\frac{\partial X^*}{\partial t_1} \right)^{NT}$ and $\left(\frac{\partial \bar{E}_1^*}{\partial t_1} \right)^T > \left(\frac{\partial \bar{E}_1^*}{\partial t_1} \right)^{NT}$.

As is shown in Remark 3 the strategic effect is larger in absolute terms when tradable permits are in place. The reason relies again on the fact that the marginal abatement cost for the global pollutant under tradable permits is fixed at the permits price level and does not respond to the increase in production. On the contrary, when permits are non-tradable,

Fig. 2 Endogenous permits price

the marginal abatement cost of the global pollutant increases following an increase in production and thus mitigates the effectiveness of an initial decrease in t_1 . Notably, the effect of a change in the domestic local tax over the foreign local emissions is equivalent to the corresponding one in production. This follows simply from the fact that a change in the local tax affects foreign production but not the foreign abatement level. It can be shown that, in equilibrium, we end up with higher levels of local pollution, lower profits, and lower welfare in each country.

5.4 Endogenous Permits Price

The permits price P^e is the one that clears the international permits market, which might cover many different sectors, so it is natural to assume price-taking behavior. This is consistent with Requate (2006) where he argues that, especially for pollutants like CO_2 , CO , and NO_x , competitive behavior in the permits market can be justified if there are other firms outside the oligopolistic industry that operate in the same permit market. Indeed, the EU ETS scheme includes almost half of the EU's CO_2 emissions from more than 11,000 installations across all 28 member states.¹¹ As Doda et al. (2018) also argue, steps have

¹¹ Even in the absence of other participants in the permits market, price-taking behavior is a widely used assumption in the literature (Sartzetakis 1997; Malueg and Yates 2009; Meunier 2011; Antoniou et al. 2014).

been taken forward to link markets concerning the same or even different pollutants and this will create thicker markets for permits where the price will be less dependent on local policy changes.

Here, we cast doubt on this assumption. It is important to distinguish between the notions of endogenous price and that of market power. The first implies that the permits price is determined by a reduced version of an equation such as $e_2 + E_2 = 0$. The second shows that when the firms maximize their profits with respect to the number of permits they are willing to trade, they do recognize that their decisions influence the price. For example, the first-order condition of the domestic firm with respect to the number of permits presented in Eq. (4) is now $\pi_{e_2} = P^e + \frac{\partial P^e}{\partial e_2} e_2 - c_{e_2}(\cdot) = 0$. These two may co-exist. We first focus on the endogenous market price to see how our results are affected and then we argue that allowing also for market power, at least for the purposes of our study, is immaterial. To this end we consider the most extreme case where the two exporting firms are the only players. For illustrative purposes we set $\gamma = 0$.

Figure 2 introduces the demand and supply for permits from the two firms. The positively sloped curves denote the marginal abatement costs of the transboundary pollutant of the home firm, i.e., $c_{a_2}(a_2) = c_{2a_2}(a_2)$, whereas the negatively sloped curves denote the corresponding ones of the foreign firm, i.e., $C_{A_2}(A_2) = C_{2A_2}(A_2)$. On the horizontal axis from left to right, we measure the number of permits that the domestic firm is willing to sell (supply of permits) or purchase (demand for permits), i.e., e_2 . From right to left, we measure the number of permits that the foreign firm is willing to trade (supply of permits), i.e., E_2 . Naturally, changing e_2 and E_2 affects the marginal costs of abatement through Eq. (1). Before any change is realized, the permits market is assumed to be in equilibrium at point A (the two marginal abatement costs are equal to P^e) where no permits trading takes place due to symmetry, i.e., $e_2 = E_2 = 0$.

We now consider a change in the domestic policy for the local pollutant, e.g., an increase in the emissions cap $\bar{e}_1$ which lowers $c_{1a_1}(a_1)$. This tends to increase output, which through Eq. (1) increases the abatement of the global pollutant and its corresponding marginal abatement costs, $c_{2a_2}(a_2)$. This move is represented graphically by an upward shift of the corresponding marginal abatement cost function from the positively sloped solid line to the dashed one. The higher marginal costs imply that for a price equal to P^e the firm is willing to purchase permits, i.e., $e_2 < 0$. Higher domestic output decreases the corresponding foreign one because of the reaction function of output. This reduces the foreign marginal abatement costs of the global pollutant, $C_{2A_2}(A_2)$, illustrated by a downward shift of the marginal abatement cost of the foreign firm (from the negatively sloped solid to the dashed line). Note that this change is lower in magnitude because the reaction function of output has a slope which in absolute terms is lower than one. A lower marginal abatement cost at the price P^e induces the foreign firm to sell permits, i.e., $E_2 > 0$. Given that the changes in the marginal abatement costs of the two firms are of different magnitudes it follows that the domestic firm is willing to purchase more permits than the corresponding allowances offered by the foreign one. Therefore, at the initial equilibrium price there exists an excess demand for permits (DE), leading to a new equilibrium price $P^{e'}$ which corresponds to the point of intersection of the new supply and demand functions (point C).

We now place our two scenarios into the current context. Under scenario *T*, it follows directly from the discussion above that while the marginal abatement costs of the domestic firm tend to be higher due to the increased levels of production they are ultimately tied at the fixed permits price and are thus equal to P^e . Scenario *NT* suggests that since there is no trading of permits the marginal abatement cost of the second pollutant

Fig. 3 Aggregate welfare levels under tradable and non-tradable permits: changes in permits price

increases (following the increase in output). Given that regulation of the global pollutant is fixed at a binding level, the domestic firm must abate the extra emissions. Graphically, this is represented by a move from A to B and the marginal abatement costs of the second pollutant equal $P^{e''}$. The difference in the marginal abatement costs of the second pollutant across the two scenarios is the driving force of our model. With an endogenous permits price, the price, in the most extreme case, increases from P^e to $P^{e'}$. This change is less pronounced than the one caused in scenario NT, i.e., P^e to $P^{e''}$. The latter leads us to the conclusion that the implications of our model carry over when the permits price is endogenous.

It is also worth mentioning that allowing the firms to exert market power in the permits market does not add anything to the analysis. In general, dealing with such a problem is cumbersome as there is an indeterminacy caused by the absence of a net supply (demand) function for permits. One way to overcome this problem is to employ the notion of supply function equilibria first introduced by Klemperer and Meyer (1989). We refer to Antoniou et al. (2014) for a specific example of this notion applied in the permits market. A key result in their study is that, in general, allowing for market power reduces the volume of permits trading. Interestingly, the permits price remains unchanged with respect to the case where the price is endogenous but there is no market power. This confirms our initial claim.

5.5 Changes in the Permits Price

It is worth considering the implications and how the results of Proposition 3 are affected as we perturb the permits price away from the one that corresponds to the non-strategic case, i.e., $P^e \neq P^{NS}$. To do so we introduce Fig. 3 which summarizes the results based on

the linear specification of our model. The two solid curves simply replicate the previous analysis. The two dashed curves represent two alternative cases where the permits price is different from the one that corresponds to the non-strategic case. In particular, for a higher permits price, i.e., $P^e > P^{eNS}$, the aggregate welfare under scenario T shifts upwards for every level of aggregate emissions. On the contrary, aggregate welfare shifts downwards when $P^e < P^{eNS}$. A higher permits price increases the marginal abatement costs and the abatement of the global pollutant undertaken by the firm. As a consequence, the firm sells permits to the other sectors, while at the same time competition is softened. This double dividend results in higher profits. Higher profits and lower pollution entail higher welfare. The opposite holds when permits prices decline.

Given the welfare analysis of our model (Proposition 3), where the equilibrium welfare is lower in scenario T compared to scenario NT , it follows immediately from the discussion above that for $P^e < P^{eNS}$ the difference between the two scenarios is magnified. Conversely, when $P^e > P^{eNS}$ welfare under scenario T increases. When the permits price rises significantly then the ordering of the equilibrium welfare levels across the two scenarios is altered. The benefits described above as a double dividend are stronger than the negative effect present in our model.

In 2013, the permits price of the EU Emissions Trading System (EU ETS) fell significantly to a record low of €2.81, opening a discussion within the EU commission as to whether to withdraw a significant number of permits. During 2015–2016 the price varied between €4 and €7, which was still much lower than the starting price of €25 in 2005, that peaked at €30 by early 2006. Thus, at the start of the third phase, a substantial allowances surplus was created of around 2 billion allowances which dropped to 1.7 billion in 2016 as a result of back loading, that followed the decision of the Commission to postpone the auctioning of 900 million allowances until 2019–2020. According to our theoretical results, a higher permits price results in higher welfare as exporting firms coordinate on lower production levels while simultaneously earning windfall profits from permit trading. Therefore, our policy prescriptions are fully aligned with the intentions of the European Commission to raise the carbon price, despite the fact that this suggestion has been opposed by individual governments. Indeed, in order to stabilize allowance price, the Commission is planning to create a market stability reserve that will adjust the number of auctioned allowances.

6 The EU ETS and Local Pollution

Our theoretical model delivers, among others, the following prediction: For a given level of the global pollutant, introducing a permits market for this pollutant leads to higher levels of local pollution as an indirect way of promoting exports. A testable hypothesis implied from our theoretical results is that the exporters that participated in the EU ETS (treatment group) will end up polluting more in terms of local pollution compared to those exporters that did not participate (control group). This is the claim of Proposition 2.

Descriptive Analysis We exploit the data provided from the survey of the European Environment Agency (EEA) at the industry level for the EU 28 countries on the levels of several local pollutants across the time period 1990–2012. The introduction of the EU ETS fits the theory presented above since during Phase I (2005–2008) the emission allowances were distributed through grandfathering, according to the previous reported

Fig. 4 EU28 Air pollutant emissions, (logarithmic scale)

emissions of the participating industries. That is, the target of the regulator for the CO_2 emissions should be the same between the years prior to the introduction of the EU ETS in 2005 and the following years (see footnote 9). Note that most of the allowances were distributed to electricity producers and combustion industries, followed by iron and steel, cement, and refineries (see Alberola et al. 2008). According to Martin et al. (2014) the European Commission decided to endow either carbon-intensive or trade-exposed industries, or both, with a high number of allowances. This complements our main prediction of the theoretical model, that introducing a tradable permits scheme is one possible channel to promote exports.

Interestingly, we focus on the year 2005 where the EU ETS was introduced and resulted in a regime switch in the regulation of CO_2 . At the same time, Annex I of the Gothenburg protocol was applied, and this created a unique opportunity to identify how the regulation of local pollution responded to this switch of the regulatory regime. To relate the

Table 3 Top European export countries, Freely allocated allowances and Verified emissions. Sources: <http://www.worldstopexports.com/top-european-export-countries/><https://www.eea.europa.eu/data-and-maps/data/european-union-emissions-trading-scheme-7>

Top European export countries		Total 1st and 2nd trading period (2005–2012)	
		Freely allocated EUAs	Verified emissions
% EU total		(Tonne of CO ₂ equ.)	
Germany	25.4	3,068,013,582	3,246,555,152
France	9.2	977,011,342	839,438,324
Netherlands	8.85	593,582,950	566,167,679
Italy	8.8	1,440,566,280	1,466,631,546
United Kingdom	7.7	1,503,515,127	1,705,565,484

information relegated above to our theory we focus on local pollution as described by the pollutants $PM_{2.5}$ and PM_{10} by several sectors introduced in Fig. 4. The interesting feature that these pollutants share is that they were initially exempted from the Gothenburg protocol. This in turn implies that the regulation of these pollutants has been under the discretion of local authorities. We use as a proxy of environmental stringency the level of emission outputs (see Brunel and Levinson 2013).

The (a) and (b) graphs in Fig. 4 present the emissions generated by industries that participate in the EU ETS. The bottom graphs (c and d) refer to non-participants. Also, graphs (a) and (c) show the emissions generated by industries that have significant exporting activity, while in graphs (b) and (d), we observe the corresponding emissions of non-export-oriented industries. The five different sectors introduced here which are both export-oriented and participate in the EU ETS are: Cement, Combustion (Non-ferrous metals, Chemicals, Food processing, Beverages and tobacco), Aluminium, Solid fuels, and other energy industries.¹² The most polluting sector that is participating in the EU ETS but is not considered to be export-oriented is Public Electricity and Heat Production. As an example of an exporting sector that does not participate in the EU ETS, we present all the activities related to Agriculture/Forestry/Fishing. Finally, the three non-participants and non-export-oriented sectors presented here are the Residential Sector and the emissions from Road Transportation and Railways. In the same figure, we place the emissions of CO₂ generated by every single sector mentioned above.

Regarding the level of local pollution from the exporting sectors that participated in the EU ETS, as presented in graphs (a1) and (a2), we can see that the overall trend since 1990 is decreasing (treatment group). Around the period when the EU ETS was introduced, in most of the examples there is an increase in the level of local pollutants which lasts until the financial turmoil of 2008. On the contrary, as we can observe from (c1) and (c2), this jump did not occur for the group of the exporting sectors that did not participate in the EU ETS (control group). This is in line with the theoretical claim presented in Proposition 2.¹³

¹² The exports of the EU countries as a percentage of the world exports are 47% for the combustion of chemicals, 43% for food processing, beverages, tobacco, 40% for aluminium, 34% for non-ferrous metals, 28% for cement, and 16% for solid fuels. The data are taken from the UN Comtrade database, apart from the export percentage of the solid fuels which was taken from the International Trade Centre. All that data refer to the exports of 2011.

¹³ In the case of the industries that participated in the EU ETS, but are not export-oriented (graphs (b)), we observe that the introduction of the permits market did not particularly affect the generated local pollution. In a similar fashion the emissions of local pollutants generated by non-exporting industries that did not participate in the EU ETS (d) have decreased over time.

One direct implication following our theoretical prediction of laxer policy regarding the local pollutant for the treatment group is that the demand for CO₂ emissions in this group and hosting countries should rise because of the introduction of the EU ETS. Indeed, these countries appear to be net buyers in the EU ETS, while the ones with lower exporting activity are sellers in the permits market. The top five European exporting countries, which account for 60% of all EU-28 export goods, surrendered 241 million trading units more than the ones that were freely allocated to them during 2005–2012. Among them, Germany, the UK, and Italy, which are the top countries with both high exporting activity and high energy intensive production, were clearly net buyers in the market during the first two trading periods. On the other hand, France and the Netherlands, which also have high exports but they have a lower energy intensive industrial activity, generated a lower number of emissions compared to the number of free allowances allocated to them. Finally, countries with lower exporting activity appear to be net sellers in the permits market. Table 3 indicates the patterns for the largest exporters in the EU through the comparison of freely allocated emission permits and verified emissions.¹⁴

Estimations Our theoretical predictions, as well as the patterns illustrated in Fig. 4, are consistent with the results of a difference-in-differences analysis. We follow this approach so as to rule out the time-invariant omitted variables missing from our dataset and control for unobserved time-varying factors that could affect *PM* emissions.¹⁵ Our panel is dynamic in the sense that emissions are persistent. Given that our time series dimension significantly exceeds the cross-sectional one, we use the Anderson–Hsiao estimator, e.g., Judson and Owen (1999). More specifically, we estimate the following regression (6) in first-differences, where *i* indexes sector and *t* indexes time:

$$PM_{i,t} = a_0 + \beta_0 PM_{i,t-1} + \gamma_0 Treat + \delta_0 (ExPart * Treat) + \varepsilon_{i,t} \quad (6)$$

The dependent variable, $PM_{i,t}$, is the level of the emissions of sector *i* in year *t*. $PM_{i,t-1}$ stands for the lagged value of the emissions. *Treat* is a dummy variable indicating whether an observation belongs to the treatment period (*Treat* = 1 for all the years after 2004). *ExPart * Treat* is an indicator variable that equals one for export-oriented participant sectors after the implementation of the EU ETS (treatment group) and zero for export-oriented non-participant sectors (control group). We omit a dummy that captures the export-oriented sectors that participated in the treatment due to collinearity. The coefficient a_0 captures the effect over $PM_{i,t}$ of the firms absent the presence of the treatment and participation. The parameter γ_0 measures how the general trend changes after 2004 for all groups. Finally, δ_0 captures the differential effect of the treatment on (export-oriented) participants versus (export-oriented) non-participants. The latter is the one that captures the potential testable hypothesis implied by Proposition 2 (see beginning of Sect. 6).

Identification comes from the fact that after controlling for any changes, *PM* levels would have evolved in the same way in treatment and control sectors. We observe from Fig. 4 (see (a) and (c)) that there is a common declining trend in aggregate, and thus average, emissions of the exporting sectors (participants and non-participants) prior to the

¹⁴ Due to the increased demand for permits from these sectors we would expect, *ceteris paribus*, a higher permits price. Initially, after the introduction of the EU ETS the permits price increased, but as described also in Sect. 4.5 it then dropped significantly. The reason is that the countries have allocated an excess number of permits in the exporting sectors. This became feasible due to the National Allocation Plan which has been recently abolished (see COM 2016).

¹⁵ Wolff (2014) also uses a difference-in-differences analysis to explore the effectiveness of the introduction of low emission zones in several German cities on the reduction of the levels of PM_{10} emissions.

Table 4 Regressions for $PM_{2.5}$ and PM_{10}

	First differences			
	Exp. participants versus non-part.	Non-export part. versus non-part.	Exp. participants versus non-part.	Non-export part. versus non-part.
	(1)	(2)	(3)	(4)
Emissions PM	0.577*** (5.383)	− 0.254 (− 1.415)	0.3105*** (2.60)	− 0.249 (− 1.34)
Treat	− 1.001** (− 2.099)	− 4.307 (− 1.415)	− 0.6916 (− 0.86)	− 1.5919 (− 0.18)
ExPart*Treat	1.420*** (2.962)		1.392* (1.73)	
NExPart*Treat		3.663 (0.562)		− 1.2538 (− 0.15)
Constant	− 0.190*** (− 2.576)	− 4.136** (− 2.506)	− 0.4209*** (− 3.49)	− 6.5866*** (− 2.85)
Observations	189	84	189	84
R ²	0.365	0.074	0.1122	0.062

t statistics in parentheses, * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

introduction of tradable permits. The results are in line with our theoretical prediction (see Proposition 2) and are presented in Table 4. In columns (1) and (2) we present the results of the regressions regarding $PM_{2.5}$. In the first column we focus on the exporting sectors that participated in the treatment versus those that did not, as described in (6). In particular, the coefficient that controls for the exporting firms that participated in the permits market (δ_0) is positive and statistically significant at the 1% level, despite the fact that the introduction of the treatment affected the aggregate emissions of these sectors negatively ($\gamma_0 < 0$). In column (2) we run a placebo regression for non-exporters that participated in the treatment versus those that did not. We run the same regression as the one introduced in (6) where instead of $ExPart * Treat$ we use $NExPart * Treat$ as a dummy variable that is equal to one for non-export sectors that participated in the EU ETS. We observe that the introduction of the policy has no significant effect on $PM_{2.5}$.

In the last two columns of Table 4 we run the same regressions with respect to PM_{10} . Here, we observe (see column 3) that the introduction of the treatment increased pollution in the exporting sectors ($\delta_0 > 0$). This is significant at the 10% level. The corresponding placebo regression yields no additional insights and confirms the previous claims (column 4).

7 Concluding Remarks

We use a model of strategic environmental policy with two pollutants, where the two firms compete à la Cournot in a third market. The transboundary pollutant is controlled at an international level, while the local pollutant is regulated unilaterally. The focus question is whether the policy targeting the local pollutant could be used as a means to promote the exports of the competing firms under the assumption that transboundary

pollution is set internationally. Our conclusion is in any case affirmative. Our findings show that when transboundary pollution is regulated through the use of emission permits then the regulator has a stronger incentive to relax the regulation regarding local pollution, compared to the case where command and control is implemented for the reduction of transboundary pollution, which entails welfare losses. We attest that export-oriented sectors that participated in the EU ETS increased the generation of local pollutants around the period of the enforcement of the trading scheme, while this trend was followed by a gradual adjustment during the following years. This pattern is not observed in the sectors that either do not have significant exporting activities or did not participate in the EU ETS.

To sum up, our results highlight the need to control for local pollution when transboundary pollution is regulated at an international level. This could prove to be very informative in the case of China and Ontario which both launched new trading schemes in 2017 with the aim of controlling transboundary pollution. Notwithstanding, we employ a trade model under multiple pollutants, our set-up could capture different scenarios characterized by an interplay between the different components of a cost function. When production requires multiple inputs, where at least one input has an infinitely elastic supply function, a similar story can be uncovered. This is the case when a binding minimum wage is introduced or if the firms have to resort to capital markets, where the interest rate is fixed in the international market, to fund their production. In all these cases the effect of the reduction in the price of a regulated input is magnified.

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Appendix 1

Proof of Proposition 1 (a) In order to determine the sign of $\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT}$ we differentiate the profit-maximizing conditions in (4) of the firms with respect to outputs and solve for the comparative statics:

$$\begin{bmatrix} \pi_{xx} & \pi_{x\bar{e}_1} \\ \pi_{Xx} & \pi_{X\bar{e}_1} \end{bmatrix} \begin{bmatrix} dx^* \\ dX^* \end{bmatrix} = \begin{bmatrix} -\pi_{x\bar{e}_1} d\bar{e}_1 \\ 0 \end{bmatrix} \Leftrightarrow \frac{dX^*}{d\bar{e}_1} = \frac{\pi_{Xx}\pi_{x\bar{e}_1}}{\Delta^{NT}}, \quad (7)$$

where Δ^{NT} is the determinant of the Hessian matrix and the condition for stability implies $\Delta^{NT} > 0$ (Dastidar 2000). Note that $\Pi_{Xx} < 0$ and $\pi_{x\bar{e}_1} = \theta_1 c_{1a_1a_1}(\cdot) + \theta_2 \gamma$. As the costs are convex it follows that for $\gamma = 0 \Rightarrow \pi_{x\bar{e}_1} > 0 \Rightarrow \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} < 0$.

Similarly to scenario *NT* we determine $\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T$. Differentiating the profit-maximizing conditions in (4) it follows:

$$\begin{bmatrix} \pi_{xx} & \pi_{xX} & \pi_{xe_2} & 0 \\ \Pi_{Xx} & \Pi_{XX} & 0 & \Pi_{XE_2} \\ \pi_{e_2x} & 0 & \pi_{e_2e_2} & 0 \\ 0 & \Pi_{E_2X} & 0 & \Pi_{E_2E_2} \end{bmatrix} \begin{bmatrix} dx^* \\ dX^* \\ de_2^* \\ dE_2^* \end{bmatrix} = \begin{bmatrix} -\pi_{x\bar{e}_1} \\ 0 \\ -\gamma \\ 0 \end{bmatrix} d\bar{e}_1 \Leftrightarrow$$

$$\frac{dX^*}{d\bar{e}_1} = \frac{\Pi_{Xx}\Pi_{E_2E_2}(\pi_{x\bar{e}_1}\pi_{e_2e_2} - \gamma\pi_{e_2x})}{\Delta^T}, \quad (8)$$

where Δ^T is the determinant of the Hessian matrix. Following Bulow et al. (1985) in order to ensure the stability of the equilibrium, the Hessian matrix must be negative definite which implies that $\Delta^T > 0$. Moreover, the conditions for the uniqueness of the equilibrium in this set-up are satisfied as long as the cost function is convex (see Meunier 2011). We know that $\Pi_{Xx}\Pi_{E_2E_2} > 0$ and $\pi_{x\bar{e}_1}\pi_{e_2e_2} - \gamma\pi_{e_2x} = \theta_1[\gamma^2 - c_{1a_1a_1}(\cdot)c_{2a_2a_2}(\cdot)] < 0$ (see footnote 6) $\Rightarrow \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T < 0$.

(b) For $\gamma = 0$ the strategic effects in (7) and (8) are as follows:

$$\begin{aligned} \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} &= \frac{\Pi_{Xx}\pi_{x\bar{e}_1}}{\Delta_{\gamma=0}^{NT}} = \frac{\theta_1 R_{Xx}(\cdot)c_{1a_1a_1}(\cdot)}{\Delta_{\gamma=0}^{NT}} \text{ and} \\ \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T &= \frac{\Pi_{Xx}\Pi_{E_2E_2}(\pi_{x\bar{e}_1}\pi_{e_2e_2} - \gamma\pi_{e_2x})}{\Delta_{\gamma=0}^T} = \frac{\theta_1 R_{Xx}(\cdot)c_{1a_1a_1}(\cdot)c_{2a_2a_2}(\cdot)c_{2A_2A_2}(\cdot)}{\Delta_{\gamma=0}^T}, \\ \Delta_{\gamma=0}^{NT} &= [\theta_1^2 c_{1a_1a_1}(\cdot) + \theta_2^2 c_{2a_2a_2}(\cdot) - r_{xx}(\cdot)] [\theta_1^2 c_{1A_1A_1}(\cdot) + \theta_2^2 c_{2A_2A_2}(\cdot) - R_{XX}(\cdot)] - r_{xX}(\cdot)R_{Xx}(\cdot) \text{ and} \\ \Delta_{\gamma=0}^T &= c_{2a_2a_2}(\cdot)c_{2A_2A_2}(\cdot) [(\theta_1^2 c_{1a_1a_1}(\cdot) - r_{xx}(\cdot))(\theta_1^2 c_{1A_1A_1}(\cdot) - R_{XX}(\cdot)) - r_{xX}(\cdot)R_{Xx}(\cdot)]. \end{aligned} \quad (9)$$

Given that in the benchmark case the level of regulation of both pollutants is the same and no permits trading takes place it follows that the equilibrium output levels are equal across the two scenarios. Then, for $\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} - \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T > 0$ it suffices to show that $\frac{1}{c_{2a_2a_2}(\cdot)c_{2A_2A_2}(\cdot)}\Delta_{\gamma=0}^T < \Delta_{\gamma=0}^{NT}$ where the subindex stands for the corresponding determinants of the Hessian matrices when $\gamma = 0$. Therefore:

$$\begin{aligned} \Delta_{\gamma=0}^{NT} - \Delta_{\gamma=0}^T &= \theta_2^2 \left[\theta_1^2 (c_{1A_1A_1}(\cdot)c_{2a_2a_2}(\cdot) + c_{1a_1a_1}(\cdot)c_{2A_2A_2}(\cdot)) + \right. \\ &\quad \left. c_{2a_2a_2}(\cdot)(\theta_2^2 c_{2A_2A_2}(\cdot) - R_{XX}(\cdot)) - c_{2A_2A_2}(\cdot)r_{xx}(\cdot) \right] > 0 \\ &\Rightarrow \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} > \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T. \end{aligned}$$

□

Proof of Proposition 2 Define as $\bar{e}_1^{*n}$, $n = T, NT$ the pollution level in equilibrium under each scenario. Given that the local pollutants are strategic substitutes (negative definite Hessian matrix) and exploiting symmetry, in equilibrium we always get that $\bar{e}_1^{*n} = \bar{E}_1^{*n}$. To show that $\bar{e}_1^{*T} > \bar{e}_1^{*NT}$ it is sufficient to illustrate that the strategic component in (5) is larger in the first case, i.e., $\left(\frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \bar{e}_1}\right)^T > \left(\frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} \Leftrightarrow \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T < \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT}$ since $\left(\frac{\partial \pi^*}{\partial X^*}\right)^T = \left(\frac{\partial \pi^*}{\partial X^*}\right)^{NT}$. $\square$

Proof of Proposition 3 The first-order conditions for a maximum are the following:

$$\left(\frac{dw^j}{d\bar{e}_1}\right)^n = \frac{\partial \pi^*}{\partial \bar{e}_1} + \frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \bar{e}_1} + \frac{\partial \Pi^*}{\partial x^*} \frac{\partial x^*}{\partial \bar{e}_1} - \frac{\partial d}{\partial \bar{e}_1} = 0 \text{ and } \bar{e}_1^* = \bar{E}_1^*. \quad (10)$$

It is important to note that, by construction, $(w^j)^T = (w^j)^{NT}$ in the non-strategic case. Irrespective of the scenario $\frac{\partial x^*}{\partial \bar{e}_1} > \left|\frac{\partial X^*}{\partial \bar{e}_1}\right|$. Therefore, $\bar{e}_1^{c*} < \bar{e}_1^*$ where the index c stands for pollution in the cooperative solution. For values of pollution which are higher than $\bar{e}_1^{c*}$ it follows that $\frac{dw^j}{d\bar{e}_1} < 0$. To show that in the strategic case $(w^{j*})^{NT} > (w^{j*})^T$ which implies $(w^*)^{NT} > (w^*)^T$ it suffices that $\left(\frac{dw^j}{d\bar{e}_1}\right)^{NT} > \left(\frac{dw^j}{d\bar{e}_1}\right)^T$ for values of $\bar{e}_1$ close to the non-strategic equilibrium. This is true iff $\left(\frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \bar{e}_1} + \frac{\partial \Pi^*}{\partial x^*} \frac{\partial x^*}{\partial \bar{e}_1}\right)^{NT} > \left(\frac{\partial \pi^*}{\partial X^*} \frac{\partial X^*}{\partial \bar{e}_1} + \frac{\partial \Pi^*}{\partial x^*} \frac{\partial x^*}{\partial \bar{e}_1}\right)^T \Leftrightarrow \left(\frac{\partial X^*}{\partial \bar{e}_1} + \frac{\partial x^*}{\partial \bar{e}_1}\right)^{NT} < \left(\frac{\partial X^*}{\partial \bar{e}_1} + \frac{\partial x^*}{\partial \bar{e}_1}\right)^T \Leftrightarrow \left[\frac{\partial X^*}{\partial \bar{e}_1} \left(1 + \left(\frac{\partial X^*}{\partial x^*}\right)^{-1}\right)\right]^{NT} < \left[\frac{\partial X^*}{\partial \bar{e}_1} \left(1 + \left(\frac{\partial X^*}{\partial x^*}\right)^{-1}\right)\right]^T$. Given $\left(1 + \left(\frac{\partial X^*}{\partial x^*}\right)^{-1}\right)^{NT} = \left(1 + \left(\frac{\partial X^*}{\partial x^*}\right)^{-1}\right)^T < 0 \Rightarrow \left[\frac{\partial X^*}{\partial \bar{e}_1} \left(1 + \left(\frac{\partial X^*}{\partial x^*}\right)^{-1}\right)\right]^{NT} < \left[\frac{\partial X^*}{\partial \bar{e}_1} \left(1 + \left(\frac{\partial X^*}{\partial x^*}\right)^{-1}\right)\right]^T \Leftrightarrow \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} > \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T$ which from Proposition 1b holds true. $\square$

Appendix 2

Proof of Remark 1 *NT*: We employ the corresponding first-order conditions provided in (4). They reduce to the following open forms:

$$\left\{ \begin{array}{l} \pi_x = B - b(2x + X) - (g_1 + \gamma)(x - \bar{e}_1) - (g_2 + \gamma)(x - \bar{e}_2) = 0 \\ \Pi_X = B - b(2X + x) - (g_1 + \gamma)(X - \bar{E}_1) - (g_2 + \gamma)(X - \bar{E}_2) = 0 \end{array} \right\}. \quad (11)$$

Then, solving the system of equations in (11) we obtain the stage 2 equilibrium outputs:

$$\left\{ \begin{array}{l} (x^*)^{NT} = \frac{B(b + \sum_{i=1}^2 g_i + 2\gamma) + (\sum_{i=1}^2 g_i + 2\gamma) \sum_{i=1}^2 (g_i + \gamma) \bar{e}_i - b \sum_{i=1}^2 (g_i + \gamma) (\bar{E}_i - 2\bar{e}_i)}{(b + \sum_{i=1}^2 g_i + 2\gamma)(3b + \sum_{i=1}^2 g_i + 2\gamma)} \\ (X^*)^{NT} = \frac{B(b + \sum_{i=1}^2 g_i + 2\gamma) + (\sum_{i=1}^2 g_i + 2\gamma) \sum_{i=1}^2 (g_i + \gamma) \bar{E}_i - b \sum_{i=1}^2 (g_i + \gamma) (\bar{e}_i - 2\bar{E}_i)}{(b + \sum_{i=1}^2 g_i + 2\gamma)(3b + \sum_{i=1}^2 g_i + 2\gamma)} \end{array} \right\}. \quad (12)$$

From the second equation in (12) we directly infer the strategic effect for *NT*:

$$\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} = -\frac{b(g_1 + \gamma)}{\left(b + \sum_{i=1}^2 g_i + 2\gamma\right)\left(3b + \sum_{i=1}^2 g_i + 2\gamma\right)}. \quad (13)$$

T : We employ the corresponding first-order conditions provided in (4). They reduce to the following open forms:

$$\left\{ \begin{array}{l} \pi_x = B - b(2x + X) - (g_1 + \gamma)(x - \bar{e}_1) - (g_2 + \gamma)(x - \bar{e}_2 + e_2) = 0 \\ \Pi_X = B - b(2X + x) - (g_1 + \gamma)(X - \bar{E}_1) - (g_2 + \gamma)(X - \bar{E}_2 + E_2) = 0 \\ \pi_{e_2} = P^e - g_2(x - \bar{e}_2 + e_2) - \gamma(x - \bar{e}_1) = 0 \\ \Pi_{E_2} = P^e - g_2(X - \bar{E}_2 + E_2) - \gamma(X - \bar{E}_1) = 0 \end{array} \right\}. \quad (14)$$

Then, solving the system of equations in (14) we obtain the stage 2 equilibrium outputs:

$$\left\{ \begin{array}{l} (x^*)^T = \frac{Bg_2[(b + g_1)g_2 - \gamma^2] + (g_1g_2 - \gamma^2)[g_2(g_1\bar{e}_1 - P^e) - \gamma(P^e + \gamma\bar{e}_1)] - b g_2[(g_2 + \gamma)P^e - (g_1g_2 - \gamma^2)(2\bar{e}_1 - \bar{E}_1)]}{(3bg_2 + g_1g_2 - \gamma^2)[(b + g_1)g_2 - \gamma^2]} \\ (X^*)^T = \frac{Bg_2[(b + g_1)g_2 - \gamma^2] + (g_1g_2 - \gamma^2)[g_2(g_1\bar{E}_1 - P^e) - \gamma(P^e + \gamma\bar{E}_1)] - b g_2[(g_2 + \gamma)P^e - (g_1g_2 - \gamma^2)(2\bar{E}_1 - \bar{e}_1)]}{(3bg_2 + g_1g_2 - \gamma^2)[(b + g_1)g_2 - \gamma^2]} \end{array} \right\}. \quad (15)$$

From the second equation in (15) we directly infer the strategic effect for T :

$$\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T = -\frac{bg_2(g_1g_2 - \gamma^2)}{(3bg_2 + g_1g_2 - \gamma^2)[(b + g_1)g_2 - \gamma^2]}. \quad (16)$$

Taking the difference between the two strategic effects in (13) and (16) we get:

$$\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} - \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T = -\frac{b(g_2 + \gamma)\omega}{\left(b + \sum_{i=1}^2 g_i + 2\gamma\right)\left(3b + \sum_{i=1}^2 g_i + 2\gamma\right)\left(3bg_2 + g_1g_2 - \gamma^2\right)\left[(b + g_1)g_2 - \gamma^2\right]},$$

where $\omega \equiv [3b^2g_2\gamma - (g_1g_2 - \gamma^2)(4bg_2 + g_2^2 + 3g_2\gamma + \gamma^2 + g_1(2g_2 + \gamma))]$.

For $\gamma < 0$, given that $|\gamma| < g_1, g_2$ it follows directly that $\omega < 0 \Rightarrow \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} - \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T > 0$.

When $g_2 < |\gamma| < g_1$ it follows that $\omega > 0 \Rightarrow \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} - \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T < 0$.

For $\gamma \geq 0$ the sign of ω is ambiguous. If $\gamma = 0$ then $\omega < 0 \Rightarrow \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} > \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T$. For $\gamma = \gamma_2 \Rightarrow \omega > 0$. Given that $\omega_{\gamma\gamma} > 0$ for $\gamma > 0$, there exists a $\bar{\gamma} \in (0, \gamma_2)$: $\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} = \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T$. For $\gamma \in [0, \bar{\gamma}) \Rightarrow \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} < \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T$. For $\gamma \in [\bar{\gamma}, \gamma_2) \Rightarrow \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} \leq \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T$. $\square$

Proof of Remark 2 *NT*: Instead of g_1 and g_2 we introduce G_1 and G_2 in the second equation of (11) and then by solving the system of equations we obtain stage 2 equilibrium outputs:

$$\begin{cases} (x^*)^{NT} = \frac{B(b + \sum_{i=1}^2 G_i) + \sum_{i=1}^2 G_i \sum_{i=1}^2 g_i \bar{e}_i + b \sum_{i=1}^2 (2g_i \bar{e}_i - G_i \bar{E}_i)}{3b^2 + \sum_{i=1}^2 G_i \sum_{i=1}^2 g_i + 2b \sum_{i=1}^2 (g_i + G_i)} \\ (X^*)^{NT} = \frac{B(b + \sum_{i=1}^2 g_i) + \sum_{i=1}^2 g_i \sum_{i=1}^2 G_i \bar{E}_i + b \sum_{i=1}^2 (2G_i \bar{E}_i - g_i \bar{e}_i)}{3b^2 + \sum_{i=1}^2 G_i \sum_{i=1}^2 g_i + 2b \sum_{i=1}^2 (g_i + G_i)} \end{cases} \quad (17)$$

From (17) follows:

$$\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} = -\frac{bg_1}{3b^2 + \sum_{i=1}^2 G_i \sum_{i=1}^2 g_i + 2b \sum_{i=1}^2 (g_i + G_i)}. \quad (18)$$

T: Instead of g_1 and g_2 we introduce G_1 and G_2 in the second and fourth equations of (14) and then by solving the system of equations we obtain stage 2 equilibrium outputs:

$$\begin{cases} (x^*)^T = \frac{B(b + G_1) - G_1 P^e + g_1 G_1 \bar{e}_1 - b(P^e - 2g_1 \bar{e}_1 + G_1 \bar{E}_1)}{3b^2 + G_1 g_1 + 2b(g_1 + G_1)} \\ (X^*)^T = \frac{B(b + g_1) - g_1 P^e + g_1 G_1 \bar{E}_1 - b(P^e - 2G_1 \bar{E}_1 + g_1 \bar{e}_1)}{3b^2 + G_1 g_1 + 2b(g_1 + G_1)} \end{cases} \quad (19)$$

From (19) it follows that:

$$\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T = -\frac{bg_1}{3b^2 + G_1 g_1 + 2b(g_1 + G_1)}. \quad (20)$$

Taking the difference between the two strategic effects in (18) and (20) we get:

$$\left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^{NT} - \left(\frac{\partial X^*}{\partial \bar{e}_1}\right)^T = \frac{bg_1 [2b(g_2 + G_2) + G_2 \sum_{i=1}^2 g_i + g_2 G_1]}{[3b^2 + G_1 g_1 + 2b(g_1 + G_1)] [3b^2 + \sum_{i=1}^2 G_i \sum_{i=1}^2 g_i + 2b \sum_{i=1}^2 (g_i + G_i)]} > 0.$$

$\square$

Proof of Remark 3 *NT*: We first introduce the profit and the welfare functions when emission taxes are implemented for the local pollutant and non-tradable permits for the global one.

$$\pi = [B - b(x + X)]x - \frac{1}{2}g_1\alpha_1^2 - \frac{1}{2}g_2(x - \bar{e}_2 + e_2)^2 - t_1(x - \alpha_1) + P^e e_2, \quad (21)$$

$$w = \pi + t_1(x - \alpha_1) - d(\cdot). \quad (22)$$

Note that here it holds $e_2 = E_2 = 0$. The first-order conditions for profit maximization with respect to output and abatement for the local pollutant are the following:

$$\left\{ \begin{array}{l} \pi_x = B - b(2x + X) - g_2(x - \bar{e}_2 + e_2) - t_1 = 0 \\ \pi_{\alpha_1} = t_1 - g_1\alpha_1 = 0 \\ \Pi_X = B - b(x + 2X) - g_2(x - \bar{E}_2 + E_2) - T_1 = 0 \\ \Pi_{A_1} = T_1 - g_1A_1 = 0 \end{array} \right\}. \quad (23)$$

Solving this system of equations we obtain the second period equilibrium outputs and local emissions:

$$\left\{ \begin{array}{l} (x^*)^{NT} = \frac{B(b+g_2)-(2b+g_2)t_1+bT_1}{(b+g_2)(3b+g_2)}, (\bar{e}_1^*)^{NT} = (x^*)^{NT} - \frac{t_1}{g_1} \\ (X^*)^{NT} = \frac{B(b+g_2)-(2b+g_2)T_1+bt_1}{(b+g_2)(3b+g_2)}, (\bar{E}_1^*)^{NT} = (X^*)^{NT} - \frac{T_1}{g_1} \end{array} \right\}. \quad (24)$$

From (24) it follows

$$\left(\frac{\partial X^*}{\partial t_1} \right)^{NT} = \left(\frac{\partial \bar{E}_1^*}{\partial t_1} \right)^{NT} = \frac{b}{(b + g_2)(3b + g_2)}. \quad (25)$$

T: The first-order conditions for profit maximization with respect to output and abatement for the local pollutant are given by Eq. (23). The corresponding ones for permits are the following:

$$\left\{ \begin{array}{l} \pi_{e_2} = P^e - g_2(x - \bar{e}_2 + e_2) = 0 \\ \Pi_{E_2} = P^e - g_2(X - \bar{E}_2 + E_2) = 0 \end{array} \right\}. \quad (26)$$

Solving the equations in (23) and (26) we obtain the second period equilibrium outputs and local emissions:

$$\left\{ \begin{array}{l} (x^*)^T = \frac{B-P^e-2t_1+T_1}{3b}, (\bar{e}_1^*)^T = (x^*)^T - \frac{t_1}{g_1} \\ (X^*)^T = \frac{B-P^e-2T_1+t_1}{3b}, (\bar{E}_1^*)^T = (X^*)^T - \frac{T_1}{g_1} \end{array} \right\}. \quad (27)$$

From (27) it follows

$$\left(\frac{\partial X^*}{\partial t_1}\right)^{NT} = \left(\frac{\partial \bar{E}_1^*}{\partial t_1}\right)^{NT} = \frac{1}{3b}. \quad (28)$$

Comparing (25) with (28) we obtain:

$$\left(\frac{\partial X^*}{\partial t_1}\right)^{NT} - \left(\frac{\partial X^*}{\partial t_1}\right)^T = \left(\frac{\partial \bar{E}_1^*}{\partial t_1}\right)^{NT} - \left(\frac{\partial \bar{E}_1^*}{\partial t_1}\right)^T = -\frac{g_2[4b + g_2]}{3b(b + g_2)(3b + g_2)} < 0. \quad (29)$$

□

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