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Optimal Tax Policies under Two-Stage Clean-Up, Cross-Border Pollution and Capital Mobility

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Abstract

The literature has identified cross-border pollution, capital mobility and two-stage clean-up as the key features in the "trade Vs environment" debate, yet no study examines all three simultaneously. We build a two country trading block model with cross-border pollution and free movements of goods and capital between the two countries. Pollution reduces welfare and there is simultaneous private and public pollution abatement. Public pollution abatement is financed with the use of lump-sum and pollution tax revenue. We derive the Nash and cooperative lump-sum and pollution taxes. We, also, examine how cross-border pollution and capital mobility affect each country's optimal tax policies. Finally, we examine how the existence of capital mobility alters the effectiveness of pollution taxes on net pollution.

Keywords: *Optimal Taxes, Two-stage Clean-Up, Cross-Border Pollution, Capital Mobility.*
JEL Classification: *F18, F22, and H21*

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1 Introduction

One of the emerging modern challenges to the free-trade doctrine, raised by environmentalists and ecologically conscious groups, is the relation between freer international trade in goods and factors of production, and the quality of the environment. Seeking the roots of this "trade vs environment" debate one may invoke several points of concern. For example, one argument maintains that given the trade induced specialization many countries' comparative advantage lies in the production of so-called pollution-intensive goods. Thus, excessive production of such goods raises the levels of pollution emissions in these countries. It is also argued that given that pollution emissions are not confined by national geographic boundaries, excessive pollution generated in one country is likely to have important adverse environmental implications for neighboring countries, or for the international community at large, via cross-border spillovers. On the other hand, different countries have different preferences with respect to environmental quality. Advanced-developed economies, by and large, are not only concerned with the quantity of goods and services consumed, but also with the quality of living standards of their residents. Therefore, they adopt stringent environmental or trade related policy measures (e.g., pollution taxes and/or quotas, tariffs or import quotas) to preserve the quality of the environment. At the other end of the spectrum, it is argued that, by and large less-developed countries are becoming so-called "pollution havens" by adopting lax environmental regulations in their effort to attract foreign capital. As a result, a number of international conferences has been staged (e.g., the UN conferences in Rio de Janeiro in 1992 and in Kyoto in 1997, the OECD conference of foreign direct investment (FDI) and the environment in the Hague in 1999) in order to address these issues.[1]

In light of the above issues, we briefly review the existing theoretical literature relevant to the present work. First, there is a strand examining the welfare and policy implications of cross-border pollution e.g., Markusen (1975a), Copeland and Taylor (1995), Copeland (1996), Ludema and Wooton (1997), Ludema and Wooton (1994), Beghin, Roland-Holst, and der Mensbrugghe (1997), Silva (1997), Silva and Caplan (1997), Turunen-Red and Woodland (1998).

A common analytical assumption in the above studies is that pollution, a by-product

[1] Jaffe, Peterson, Portney, and Stanvis (1995), Grossman and Krueger (1993), Tobey (1990) and Antweiler, Copeland, and Taylor (2001) argue that the empirical evidence does not support the "pollution haven" hypothesis.

of production, is entirely abated by the private sector in response to emission taxes on private producers.[2] More often than not, however, pollution emissions are abated partly by the private and partly by the public sector of a country.[3] Ample empirical evidence shows that the share of public abatement expenditure in total abatement expenditure is sizeable and it varies among countries and from one type of pollution to another.[4] Thus, it is important that both types of abatements are taken into consideration in analyzing environmental policies. Moreover, the existence of public abatement brings in an additional instrument at the disposal of the policy maker for combating pollution on top of the standard instruments such as an emission tax, in the form of funds made available for public abatement activities. The existence of multiple instruments in turn raises the question as to how exactly the aforesaid funds are raised by the policy maker.[5] Considerable evidence suggests that emission taxes are often earmarked for pollution activities by governments.[6] As a result, a second and relatively recent strand of this literature allows for the coexistence of private and public sector pollution abatement, where the latter activity is financed through emission tax revenue earmarked for public sector pollution abatement activities. For example, Hatzipanayotou, Lahiri, and Michael (2000) in a North-South model of cross-border pollution examine how the North can influence pollution emission policies in the South, the sole generator of pollution, by the strategic use of international transfers. Khan (1996) analyzes a model with public pollution abatement only and Chao and Yu (1999) develop a model in which public pollution abatement coexists with private pollution abatement.[7]

[2] Markusen, Morey, and Olewiler (1993) report a number of examples of pollution taxes. Those include a 1988 tax on fuels in the Netherlands, a 1990 French air pollution tax and a 1990 US tax on the ozone-depleting factor of a variety of chlorofluorocarbons.

[3] This joint clean-up activity by the two sectors is what we refer to as the "two-stage clean-up".

[4] According to OECD statistics, as far as abatement of water pollution in the early 1990s is concerned, the share of public expenditure in the total expenditure is 66% in the USA and the Netherlands and only 12% in the UK. As for abatement of air pollution, the share of public abatement in the Netherlands and the UK is 55% and 30% respectively, but it is only 6% in the case of the USA.

[5] The number of policy instruments determines whether the first-best policy is achievable. Markusen (1975b) reports that in the absence of a second instrument pollution taxes can be higher or lower than the first-best taxes.

[6] For example, Brett and Keen (2000) note that, in the US, it is quite customary for environment taxes to be earmarked for specific environment related public expenditure. In particular, such tax proceeds are commonly paid into trust funds that finance various clean-up activities, or are spend on road and public transport networks.

[7] The relationship, in terms of model formulation and analysis, between the present paper and that of Chao and Yu (1999) ends with this feature of co-existence of pollution abatement by the two sectors.

Another strand of the relevant literature combines environmental issues and the international mobility of factors, particularly that of capital. It is argued that capital is prone to inter-country or regional movements due to differences in environmental policies and regulations.[8] It is, also, feared that due to environmental capital flight, pollution-intensive production is concentrated to certain countries/regions, so-called "pollution havens", with lax environmental controls. Another concern is that in an effort to attract foreign capital these countries/regions may race to the bottom in their environmental regulation.[9] These and related considerations have lead to a theoretical literature on environmentally induced capital flight, of which we note the following contributions. Merrifield (1988) in a two-country general equilibrium model with international flows of goods, capital and pollution examines appropriate abatement strategies for reducing cross-border pollution. It is shown, among other things, that an attempt to reduce pollution by means of higher pollution taxes may raise pollution. Copeland (1994) examines environmental and trade policy reforms in the context of a polluted small open economy without cross-border pollution. It is shown, among other things, that when (some) factors are internationally mobile the welfare gains of a small equiproportionate reform of pollution taxes are at least as large as when factor mobility is restricted. Copeland and Taylor (1997) construct a two-good (a labor-using "clean" good and a capital-using "dirty" good) North-South model (North is richer and relatively capital-abundant) with local pollution. Within this framework they demonstrate that (i) free trade and no international capital mobility raise (reduce) world pollution relative to autarky when the North exports the clean (dirty) good, and (ii) allowing also for free international capital mobility world pollution rises (falls) when the North initially exports the dirty (clean) good.[10]

The present paper attempts a synthesis and generalization of the three aforementioned strands of the literature on the interactions between cross-border pollution, two-stage clean-up and capital mobility. To this end, we construct a general equilibrium model

[8] For example, Gray (1997) using US data finds significant negative correlation between new plants location and inter-state differences in environmental regulation.

[9] Rauscher (1991) notes that, in the absence of cross-border pollution, such competition among countries/regions may not pose a problem from an economic theory point of view, as long as it reflects the countries/regions preferences. But, with cross-border pollution, matters may actually be different, since a country with tight environmental controls suffers the consequences of such policies (e.g., lower capital endowment) but may not enjoy their benefits (i.e., cleaner environment).

[10] In a different context Rauscher (1997), Chao and Yu (1998) and Chao and Yu (2000) raise other issues regarding the interaction between international capital mobility and locally abated pollution.

of, what we call a trading block, comprising two countries with free commodity, and capital flows between them. We assume that pollution, a by-product of production, generated in each country is transmitted across borders, and it is abated partly by the private producers, in response to an emissions tax, and partly by the local government through an imported, from the rest of the world, good used by the public sector for its pollution abatement activities. Governments finance the imports of this good through lump-sum and pollution tax revenue earmarked by the public sector for its pollution abatement activity. Within this context, we examine the effects of raising lump-sum or pollution taxes on the levels of pollution and welfare. We also derive the optimal lump-sum and pollution taxes when the two countries act cooperatively in maximizing their joint welfare, and when they act non-cooperatively (Nash) maximizing own national welfare. The analysis also emphasizes the role of intra-block capital mobility for the size of the optimal cooperative/non-cooperative taxes, and on the effectiveness of pollution taxes on net pollution in each country.[11]

2 The Analytical Framework

2.1 The Model

We develop a general equilibrium model of two small open economies, home and foreign, which trade freely with each other and the rest of the world.[12] As a result, commodity prices in the two countries are constant and equal to the world commodity prices. In both countries pollution of the eyesore type is generated as a by-product of production, and it is transmitted across national borders. Identical residents, inhabiting each country, are adversely affected and suffer disutility from locally generated pollution and from pollution emitted by foreign producers and transmitted across borders.

We conjecture that the model may resemble the case of a trading block between two countries –either both developed (e.g., EU countries) or one developed and one developing

[11] Rauscher (1991) using a similar model with two countries, one good, cross-border pollution but without public pollution abatement examines the effects of increased capital mobility on the optimal levels of quantitative environmental restrictions (i.e., pollution quotas) regulated by the governments. It is shown that when the two countries act non-cooperatively, increased capital exports, facilitated by lower costs of cross-border capital mobility, move capital to the country with less restrictive environmental regulations. Global pollution, however, may be higher or lower relative to the initial situation.

[12] Following standard convention we denote with an asterisk all the variables of the foreign country.

(e.g., NAFTA agreement)– *vis-à-vis* the rest of the world. In such a context, there is free commodity trade among the block's member countries, and nearly free commodity trade between the trading block and the rest of the world. With respect to the flows of factors of production, capital is by and large freely mobile within the borders of the trading block, but it may not be as freely mobile between the trading block and the rest of the world. Finally, mobility of other factors of production, such as labor, may be restricted both among the member countries, and between the trading block and the rest of the world.[13] Here for analytical simplicity and tractability of the results, it is assumed that all factors other than capital are intra-block and internationally immobile.

We proceed to develop the model of the home, capital-importing, country; the model of the foreign, capital-exporting, country follows analogously. The home country's maximum value of production of private goods is denoted by the restricted Gross Domestic Product (GDP), or restricted revenue, function $R(p, t, K)$ defined as:

$$R(p, t, K) = \max_{x,z,K}\{p^{'}x - tz : (x, z, K) \in \Phi(v, K)\}, \tag{1}$$

where p is the vector of exogenously given world commodity prices, $\Phi(v, K)$ is the country's aggregate technology set, v is the endowment vector of the immobile factors, K is the domestic supply of capital, x is the vector of net outputs, and z is the amount of pollution emission by the private sector, net of the amount abated by the private sector.[14] In the present analysis, since (v) and (p) are invariant, for notational simplification the GDP function is written as $R(t, K)$. We assume that the $R(t, K)$ function is strictly concave in K ($R_{KK} < 0$) and strictly convex in t ($R_{tt} > 0$). The latter assumption implies that a higher emission tax level lowers the amount of pollution emissions by the private sector. By the envelop theorem, the partial derivative of the GDP function with respect to K, i.e., R_K is the marginal revenue product of capital. Also by the envelop theorem, the level of pollution, z, generated by the private sector is given by[15]

$$z = -R_t(t, K). \tag{2}$$

For the rest of the analysis we assume that pollution is capital intensive in both countries,

[13]Restrictions in the intra-block mobility of other factors such as labor are mostly due to cultural, social and other non-economic reasons.

[14]For simplicity we assume only one type of pollution emission generated in one or more sectors. A prime ($'$) denotes a transposed vector or matrix, and $p^{'}x - tz$ is the value of factor income. Finally, $\Phi(v, K)$ includes production technologies and abatement technologies in various private sectors, as they carry out some pollution abatement in response to the emission tax (t).

[15]Copeland (1994) and Turunen-Red and Woodland (1998) among others define pollution in the same way.

that is, $R_{tK} < 0$ and $R^*_{t^*K^*} < 0$.

Accounting for both private and public sector pollution abatement, the overall net pollution r, affecting the home country residents is:

$$r = z - g + \Theta(z^* - g^*) \tag{3}$$

where the parameter $\Theta \in [0, 1]$ is the rate of cross-border pollution or the spillover parameter, g is the level of public pollution abatement in the home country, and z^* and g^* denote the levels of pollution net of private abatement and the level of public pollution abatement, respectively, in the foreign country.[16]

As for the country's public sector, we assume that it imports from the rest of the world, at a constant price P_g, a commodity used to provide public pollution abatement at the level g. The cost of the imported good (*i.e.*, $P_g g$), used for public pollution abatement, is financed through the emission tax revenue (*i.e.*, $tR_t(t, K)$), earmarked for government pollution abatement activities, and through lump-sum taxes (T). Thus, the government's budget constraint is written as:

$$P_g g = -tR_t(t, K) + T. \tag{4}$$

Turning to the demand side of the economy, we assume that each country is comprised of identical individuals. Utility is adversely affected by both local and foreign pollution transmitted across borders. Let $E(u, r)$ denote the minimum expenditure required to achieve a level of utility, u, at constant prices p, omitted from the expenditure function for reasons noted earlier, and at the given level of net pollution r. The partial derivative of the expenditure function with respect to u, E_u, denotes the reciprocal of the marginal utility of income. Since pollution adversely affects household utility, the partial derivative of the expenditure function with respect to r, E_r, is positive denoting the households' *marginal willingness to pay for a reduction in pollution* (*e.g.* see Chao and Yu (1999)).[17] That is, a higher level of net pollution requires a higher level of spending on private goods to mitigate its detrimental effects so that a constant level of utility is maintained. The

[16] This formulation of additive level of net pollution, r, implies that the two countries emit the same pollutant. Generalizing the present specification to one where the two countries emit different types of pollutants only results to unwarranted algebraic complications without providing substantive analytical insight.

[17] In Copeland (1994)'s terminology, E_r is a measure of the marginal damage to consumers from pollution.

expenditure function is assumed strictly convex in r, *i.e.* $E_{rr} > 0$. That is, a higher level of net pollution raises the households' marginal willingness to pay for its reduction. It is also assumed that $E_{ru} > 0$, *i.e.* a higher level of utility increases the households' marginal willingness to pay for pollution abatement.[18]

The home, capital-importing, country's budget constraint requires that private spending $E(u, r)$ must equal factor income from the production of the private traded goods $R(t, K)$ minus repatriated earnings of foreign capital domestically employed $k^f R_K(t, K)$ and lump-sum taxes T. Thus, the income-expenditure identity for the home country is

$$E(u, r) = R(t, K) - k^f R_K(t, K) - T, \tag{5}$$

where k^f is the amount of foreign capital operating in the home country.

The model for the foreign country is similarly developed. The corresponding equations for the foreign country are

$$\begin{aligned} z^* &= -R^*_{t*}(t^*, K^*) && (6)\\ r^* &= z^* - g^* + \Theta^*(z - g) && (7)\\ P^*_{g^*} g^* &= -t^* R^*_{t^*}(t^*, K^*) + T^* && (8)\\ E^*(u^*, r^*) &= R^*(t^*, K^*) + k^f R_K(t, K) - T^*, && (9) \end{aligned}$$

where r^* is the level of total net pollution for the foreign country, Θ^* is the rate of cross-border pollution in that country; K^* is the supply of capital, and by the assumptions of the model $dK = dk^f = -dK^*$.

Finally, international capital mobility though non-existent between the trading block and the rest of the world, is perfect within the trading block, i.e., between the home and foreign countries. Since it is assumed that capital earnings are untaxed by both countries, perfect intra-block capital mobility equalizes the factor's reward in the two countries. That is, equilibrium in the trading block's capital market requires that

$$R_K(t, K) = R^*_{K^*}(t^*, K^*). \tag{10}$$

[18]This implicitly assumes that pollution abatement is a normal good.

The system of equations (2)-(10) contains nine unknowns, namely u, u^*, g, g^*, z, z^*, r, r^* and K; four –two for each country- policy parameters, namely (t, T) and (t^*, T^*); and four -two for each country- exogenous parameters, namely (P_g, Θ) and $(P^*_{g^*}, \Theta^*)$. For analytical convenience the above system is reduced to equations (4), (5), (8), (9) and (10), after appropriately substituting equations (2) and (3) into equation (5), and equations (6) and (7) into equation (9). In doing so the initial system is then solved in terms of five unknowns, namely u, u^*, g, g^*, and K. The Appendix of the paper lays out the complete comparative statics of this reduced form system.

2.2 Some Preliminary Results

For the analysis to follow, it is useful to derive the effects of taxes on the capital stock and public sector pollution abatement activities. We proceed by examining the effects of a higher domestic pollution tax (t) on these variables, while the effects of a higher foreign pollution tax (t^*) can be similarly derived.

From the Appendix it is easily derived that, under the conditions of the model, a higher pollution tax causes a capital outflow from the home country (i.e.,$(dK/dt) = \frac{-R_{tK}}{H} < 0$), and thus a capital inflow to the foreign country. The effect of the higher (t) on domestic public sector pollution abatement activity is given by

$$\Delta \frac{dg}{dt} = -HP^*_{g^*}R_t - P^*_{g^*}t(HR_{tt} - R^2_{tK}), \tag{11}$$

where $H = R^*_{K^*K^*} + R_{KK}$ and $\Delta = HP_gP^*_{g^*}$. Note that H, and Δ are negative.

Equation (11) indicates that the effect of a higher (t) on (g) is through its effect on home country government revenue. In particular, the higher (t) entails a direct positive effect on government revenue (i.e., $-\Delta^{-1}HP^*_{g^*}R_t$), which enhances the public sector's ability to provide (g), and an indirect negative effect (i.e., $-\Delta^{-1}P^*_{g^*}t(HR_{tt} - R^2_{tK})$) which mitigates its ability for the provision of (g).[19] Intuitively the direct positive effect indicates that at a given level of pollution $(-R_t)$ a higher (t) raises government revenue, and thus the level of (g) provided by the public sector. On the other hand, the higher (t) reduces government pollution tax revenue in two ways. First, it causes a reduction in R_K which in turn causes a capital outflow and the reduction in pollution. As a result, government

[19] Alternatively, equation (11) can be written as $(dg/dt) = (\partial g/\partial t) - \frac{t}{P_g}R_{tK}(dK/dt)$, where, by total differentiation of equation (4) it can be easily shown that $(\partial g/\partial t) = -(R_t + tR_{tt})$.

pollution tax revenue falls (i.e., $\Delta^{-1}P^*_{g^*}tR^2_{tK} < 0$). In addition, pollution falls as a result of the higher (t) thus exacerbating the reduction in government pollution tax revenue (i.e.,$-\Delta^{-1}P^*_{g^*}tHR_{tt} < 0$). For a small (t) an increase in its level unambiguously raises government pollution tax revenue and, thus the provision of (g), through the induced direct positive effect.

The effect of the higher (t) on foreign public sector pollution abatement activity is given by

$$\Delta\frac{dg^*}{dt} = -P_g t^* R_{tK} R^*_{t^*K^*}. \tag{12}$$

Equation (12) indicates that a higher pollution tax level by the home country raises public sector pollution abatement in the foreign country. Intuitively, a higher (t) lowers R_K, induces an inflow of capital in the foreign country, which in turn raises the level of foreign pollution. That results in higher pollution tax revenue in the foreign country, thus enhancing the public sector's ability to provide public pollution abatement.

3 Taxes, Pollution and Welfare

In this section we examine the effect of a higher domestic pollution tax (t) on net pollution in the two countries, (r) and (r^*), respectively, and on their respective levels of national welfare (u) and (u^*). Analogous results are stated for the effects of a higher tax (t^*) on the aforementioned variables. We also examine the effects of higher lump-sum taxes, T and T^* for each country respectively, on the corresponding level of national welfare.

3.1 Pollution Taxes and Net Pollution

The effect of a higher pollution (t) on domestic net pollution (r) can be derived as follows. Using equations (3), (11), (12) and the Appendix we have

$$\begin{aligned}\frac{dr}{dt} &= -(\frac{dg}{dt} + \Theta\frac{dg^*}{dt}) - [R_{tt} + (R_{tK} - \Theta R^*_{t^*K^*})\frac{dK}{dt}] \\ &= -\Delta^{-1}P^*_{g^*}(HR_{tt} - R^2_{tK})(P_g - t) - \\ &\quad \Delta^{-1}\Theta P_g R_{tK} R^*_{t^*K^*}(P^*_{g^*} - t^*) + \Delta^{-1}HP^*_{g^*}R_t.\end{aligned} \tag{13}$$

Intuitively, equation (13) shows that a higher tax (t) affects domestic net pollution (r), first through its impact on public abatement in the home and foreign countries. Second, it affects (r) through changes in domestic and foreign levels of pollution. In particular, changes in domestic pollution (z) are due to changes in the domestic pollution tax (direct effect) and changes in the domestic capital stock (indirect effect). Both effects lead to a reduction of (z). On the other hand, the higher (t) affects foreign pollution (z^*) indirectly through changes in the foreign country's capital stock (K^*). This effect increases (z^*) and through cross-border pollution it increases (r).

Equivalently, the effect of the higher pollution tax (t) on net foreign pollution (r^*) is shown to be

$$\begin{aligned} \frac{dr^*}{dt} &= -(\frac{dg^*}{dt} + \Theta^* \frac{dg}{dt}) - [\Theta^* R_{tt} + (\Theta^* R_{tK} - R^*_{t^*K^*})\frac{dK}{dt}] \\ &= -\Delta^{-1}\Theta^* P^*_{g^*}(HR_{tt} - R^2_{tK})(P_g - t) - \\ &\quad \Delta^{-1} P_g R_{tK} R^*_{t^*K^*}(P^*_{g^*} - t^*) + \Delta^{-1}\Theta^* H P^*_{g^*} R_t \end{aligned} \tag{14}$$

Observing the reduced forms of equations (13) and (14) we state sufficient conditions under which an increase in (t) reduces net pollution (r) in the home country and (r^*) in the foreign country, in the following Proposition.

Proposition 1 *Consider a two-country trading block where there is perfect intra-block capital mobility and cross-border pollution, and where pollution tax revenue in each country is earmarked for the provision of a public pollution abatement. Then, a sufficient condition for an increase in (t) to reduce (r) and (r^*) is that ($P_g > t$) in the home country and ($P^*_{g^*} < t^*$) in the foreign country.*

It is worth noting that in the absence of cross-border pollution, i.e.,$\Theta = \Theta^* = 0$, then:

1. $(dr/dt) < 0$ if only ($P_g > t$) and $(dr^*/dt) < 0$ if only ($P^*_{g^*} < t^*$), and
2. changes in one country's pollution tax affects the other country's net pollution through the induced intra-block capital mobility.

Analogous results are inferred for an increase in the foreign country's pollution tax (t^*) on the home and foreign countries' levels of net pollution.

3.2 Lump-sum Taxes, Pollution Taxes and Welfare

We start our welfare analysis of lump-sum and pollution taxes by deriving some benchmark results useful for the analysis to follow. Differentiating equation (5) gives

$$\begin{aligned} du = {} & E_r dg + \Theta E_r dg^* - [-E_r(R_{tK} - \Theta R^*_{t^*K^*}) + k^f R_{KK}]dK \\ & + [E_r R_{tt} + R_t - k^f R_{Kt}]dt + \Theta E_r R^*_{t^*t^*} dt^* - dT, \end{aligned} \tag{15}$$

where for simplicity we set $E_u = 1$. Equation (15) shows that, in the present context, a higher level of public pollution abatement at home or abroad increases welfare. The inflow of capital in the home country affects domestic welfare in two ways. First, it affects welfare positively through lower payments to foreign capital operating at home (*ie.*, $-k^f R_{KK} > 0$), and second, it affects welfare through induced changes in the levels of pollution at home and abroad (i.e.,$E_r(R_{tK} - \Theta R^*_{t^*K^*})$. In the absence of cross-border pollution (i.e., $\Theta = 0$) the inflow of capital has a negative impact on welfare through this term, but still an ambiguous one overall. On the other hand, if $\Theta > 0$, then intra-block capital mobility, which reduces K^* and lowers cross-border pollution, exerts a positive impact on welfare through the term $-E_r \Theta R^*_{t^*K^*}$.

A higher local environmental tax (t) exerts a positive impact on domestic welfare through a lower level of domestic pollution ($i.e., E_r R_{tt} > 0$), and through a lower rate of return on capital, and thus payments to foreign capital operating domestically (i.e.,$-k^f R_{Kt} > 0$). But, a higher level of (t) also exerts a negative impact on welfare since it entails the allocation of more resources to private abatement, thus the reduction of private incomes and welfare ($i.e., R_t < 0$). Finally, a higher level of the foreign environmental tax (t^*), in the presence of cross-border pollution, or a lower level of domestic lump-sum taxes (T), *ceteris paribus*, unambiguously raise home welfare. Analogous results can be derived for the foreign country by totally differentiating equation (9).

Now we turn our attention to the effects of lump-sum taxes and pollution taxes on national welfare in the two countries. In particular, using the Appendix, the effect of an increase in the domestic (foreign) lump-sum taxes on domestic (foreign) welfare is given by

$$\Delta \frac{du}{dT} = HP^*_{g^*} S_g \tag{16}$$

$$\Delta \frac{du^*}{dT^*} = HP_g S^*_{g^*}, \tag{17}$$

where $S_g \equiv (E_r - P_g)$ and $S^*_{g^*} \equiv (E^*_{r^*} - P^*_{g^*})$. We say that the public pollution abatement is locally under(over)-provided in the home country if $S_g > 0 (< 0)$, and in the foreign country if $S^*_{g^*} > 0 (< 0)$. Public pollution abatement is locally optimally provided in the home (foreign) country if $S_g = 0 (S^*_{g^*} = 0)$. That is, if $E_r = P_g$ $(E^*_{r^*} = P^*_{g^*})$. Therefore, raising lump-sum taxes, in the present context, is unambiguously welfare improving (deteriorating) if the public pollution abatement is locally under (over)-provided.

Using the Appendix and equations (15) and (13), the welfare effect of an increase in home country's pollution tax (t) on its own welfare is given by

$$\begin{aligned} \frac{du}{dt} &= R_t - E_r \frac{dr}{dt} - k^f (R_{Kt} + R_{KK} \frac{dK}{dt}) \\ &= \Delta^{-1} E_r P^*_{g^*} (HR_{tt} - R^2_{tK})(P_g - t) + \Delta^{-1} \Theta R_{tK} R^*_{t^* K^*} P_g E_r (P^*_{g^*} - t^*) \\ &+ \Delta^{-1} HP^*_{g^*} R_t (P_g - E_r) - \Delta^{-1} k^f R_{tK} R^*_{K^* K^*} P_g P^*_{g^*}. \end{aligned} \tag{18}$$

Equation (18) shows that the increase in (t) affects the home country's level of welfare in three ways. The higher (t) induces, first, a transfer of additional resources from production of goods to pollution abatement by private producers. As a result real income, and therefore, welfare is reduced (i.e., $R_t < 0$). Second, it affects (u) through changes in domestic net pollution (i.e., $-E_r \frac{dr}{dt}$). Namely, since E_r is the households' marginal willingness to pay for pollution abatement, then $-E_r \frac{dr}{dt}$ is a measure of the marginal benefit/damage of changes in (r) due to the increase in (t) on households' utility. Through this term, the increase in (t) increases (u) if $\frac{dr}{dt} < 0$ (see sufficient conditions of this result in the discussion of equation (13)). Third, the term $-k^f (R_{Kt} + R_{KK} \frac{dK}{dt})$ captures the effect of (t) on (u) through changes in payments to foreign capital operating at home. This change in payments to k^f is due to changes in the domestic marginal revenue product of capital, R_K, induced by the higher (t). Namely, by assumption, a higher (t) reduces R_K and thus payments to k^f. In addition, as previously discussed, $\frac{dK}{dt} < 0$ causing an increase in the marginal revenue product of capital and thus an increase in payments to k^f. It can be shown, however, that the positive direct effect $(-k^f R_{Kt})$ always dominates the negative indirect effect $(-k^f R_{KK} \frac{dK}{dt})$. Thus, the overall impact of (t) on (u) through changes in payments to k^f is positive, as shown by the last term, (i.e., $-\Delta^{-1} k^f R_{tK} R^*_{K^* K^*} P_g P^*_{g^*}$), of the reduced form of equation (18).

The effect of an increase in (t) on the foreign country's level of welfare is given by

$$\begin{aligned}\frac{du^*}{dt} &= -E^*_{r^*}\frac{dr^*}{dt} + k^f(R_{Kt} + R_{KK}\frac{dK}{dt}) \\ &= \Delta^{-1}\Theta^* E^*_{r^*}P^*_{g^*}(HR_{tt} - R^2_{tK})(P_g - t) - \Delta^{-1}HP^*_{g^*}\Theta^* E^*_{r^*}R_t \\ &\quad +\Delta^{-1}E^*_{r^*}P_g R^*_{t^*K^*}R_{tK}(P^*_{g^*} - t^*) + \Delta^{-1}k^f R^*_{K^*K^*}R_{tK}P_g P^*_{g^*} \end{aligned} \tag{19}$$

Equation (19) shows that an increase in (t) affects (u^*), through, first, its effect on net pollution, (r^*), and second through its effect on repatriated payments of its capital operating in the home country. The discussion of the first effect follows the discussion of equation (14), and the discussion of the second one follows that of equation (18).

Analogously, using the Appendix, the reduced form expressions of an increase in (t^*) on welfare in the foreign country (u^*) and in the home country (u) are given by the following equations

$$\begin{aligned}\Delta\frac{du^*}{dt^*} &= E^*_{r^*}P_g(HR^*_{t^*t^*} - R^{*2}_{t^*K^*})(P^*_{g^*} - t^*) + \Theta^* R_{tK}R^*_{t^*K^*}P^*_{g^*}E^*_{r^*}(P_g - t) \\ &+ HP_g R^*_{t^*}(P^*_{g^*} - E^*_{r^*}) + k^f R^*_{t^*K^*}R_{KK}P_g P^*_{g^*}, \text{ and}\end{aligned} \tag{20}$$

$$\begin{aligned}\Delta\frac{du}{dt^*} &= \Theta E_r P_g(HR^*_{t^*t^*} - R^{*2}_{t^*K^*})(P^*_{g^*} - t^*) - HP_g\Theta E_r R^*_{t^*} \\ &+ E_r P^*_{g^*}R^*_{t^*K^*}R_{tK}(P_g - t) - k^f R_{KK}R^*_{t^*K^*}P_g P^*_{g^*}\end{aligned} \tag{21}$$

The discussion of equations (20) and of (21) is analogous to that of equations (18) and of (19).

4 Optimal Lump-sum and Pollution Taxes

In this section we derive and discuss the properties of the optimal pollution taxes, (t) and (t^*) , and lump-sum taxes, T and T^*, in the two countries, under three alternative cases depending on whether or not there exists tax policy cooperation between the two countries.

4.1 Cooperative Taxes and Welfare

A standard result in the literature of environmental economics is that in the presence of cross-border pollution externalities optimal policy requires either the adoption of cooperative policies among regions/jurisdictions or the mandate of policies by a central (e.g., federal) authority.[20] Here, we begin our analysis of tax policy choices by presenting the first-best policy choices of the trading-block. This regime entails the simultaneous cooperative choice of lump-sum and pollution taxes that maximize the two countries' joint welfare. This regime constitutes a benchmark solution to which the equilibrium results to follow are compared. Even though for purposes of our analysis this case is used only as a benchmark one, in a trading block with deep economic integration (e.g., the E.U.), this may be a plausible equilibrium.

4.1.1 Cooperative Lump-sum Taxes and Welfare

The maximization of the countries' joint welfare requires setting $\frac{du}{dT} + \frac{du^*}{dT} = 0$ and $\frac{du}{dT^*} + \frac{du^*}{dT^*} = 0$, where $\frac{du}{dT}$, $\frac{du^*}{dT^*}$ are given by equations (16) and (17), respectively. Moreover, using the Appendix we get

$$\Delta \frac{du}{dT^*} = H\Theta E_r P_g \tag{22}$$

$$\Delta \frac{du^*}{dT} = H\Theta^* E^*_{r^*} P^*_{g^*} \tag{23}$$

From equations (16), (17), (22) and (23) we get that the cooperative first-best policy choice for provision of public abatement requires that

$$\bar{E}_r \equiv (E_r + \Theta^* E^*_{r^*}) = P_g \tag{24}$$

$$\bar{E}^*_{r^*} \equiv (E^*_{r^*} + \Theta E_r) = P^*_{g^*} \tag{25}$$

Intuitively, a unit of pollution generated at home causes E_r damage in the home country and $\Theta^* E^*_{r^*}$ damage in the foreign country. Thus $\bar{E}_r \equiv (E_r + \Theta^* E^*_{r^*})$ is the global (total) damage caused by a unit of locally generated pollution. Similarly $\bar{E}^*_{r^*} \equiv (E^*_{r^*} + \Theta E_r)$ is the global damage caused by a unit of foreign generated pollution. Therefore, $\bar{E}_r$ ($\bar{E}^*_r$) is the

[20] Hoel and Shapiro (2001) in a multi-regional multi-emissions model of transboundary pollution demonstrates that with free and costless population mobility amongst them, the efficient policy (eg., regional contribution to environmental degradation, local pollution taxes, and inter-regional transfers) outcome is a Nash equilibrium game among the regions. Since, however, multiple Nash equilibria are likely, policy coordination among the regions may still be necessary in order to achieve the best equilibrium.

global marginal willingness to pay for pollution abatement of the domestically (foreign) generated pollution. When $\bar{E}_r - P_g > (< 0)$ we say that the public pollution abatement in the home country is globally under-provided (over-provided), and when $\bar{E}_r = P_g$, the public pollution abatement in the home country is globally optimally provided. Similar definitions apply for the foreign country.

Equations (24) and (25) indicate that maximizing joint welfare, in the present context, requires that lump-sum taxes in each country are set at a level where the global marginal willingness to pay for pollution abatement for pollution generated in each country equals the unit cost of providing it (i.e.,$\bar{E}_r = P_g$ and $\bar{E}^*_{r^*} = P^*_{g^*}$) . Note that these two equations represent the relevant Samuelsonian rule for optimal provision of public (pollution abatement) goods. Moreover, because of the existence of cross-border pollution, the relevant Samuelsonian rule accounts not only for the marginal willingness to pay for pollution abatement within a country, but also for the marginal willingness to pay for it in the other country.

4.1.2 Cooperative Pollution Taxes and Welfare

Deriving the cooperative first-best choice of pollution taxes requires setting $\frac{du}{dt} + \frac{du^*}{dt} = 0$ and $\frac{du}{dt^*} + \frac{du^*}{dt^*} = 0$, where $\frac{du}{dt}$, and $\frac{du^*}{dt}$ are given by equations (18) and (19), respectively. Moreover, the reduced form equations for the expressions $\frac{du^*}{dt^*}$ and $\frac{du}{dt^*}$ are given by equations (20) and (21). In general, the cooperative pollution taxes for the two countries are given by

$$t_c = P_g - \frac{HP_g\bar{E}^*_r[(HR^*_{t^*t^*} - R^{*2}_{t^*K^*})P^*_{g^*}R_t\hat{S}_g - R^*_{t^*}R_{tK}R^*_{t^*K^*}P_g\hat{S}^*_{g^*}]}{\bar{E}_r\bar{E}^*_{r^*}P_gP^*_{g^*}[(HR_{tt} - R^2_{tK})(HR^*_{t^*t^*} - R^{*2}_{t^*K^*}) - R^2_{tK}R^{*2}_{t^*K^*}]} \tag{26}$$

$$t^*_c = P^*_{g^*} - \frac{HP^*_{g^*}\bar{E}_r[(HR_{tt} - R^2_{tK})P_gR^*_{t^*}\hat{S}^*_{g^*} - R_tR_{tK}R^*_{t^*K^*}P^*_{g^*}\hat{S}_g]}{\bar{E}_r\bar{E}^*_{r^*}P_gP^*_{g^*}[(HR_{tt} - R^2_{tK})(HR^*_{t^*t^*} - R^{*2}_{t^*K^*}) - R^2_{tK}R^{*2}_{t^*K^*}]} \tag{27}$$

where the denominator of equations (26) and (27) is positive, and $\hat{S}_g = \bar{E}_r - P_g$ and $\hat{S}^*_{g^*} = \bar{E}^*_{r^*} - P^*_{g^*}$. It is important to note that the cooperative pollution taxes (t_c) and (t^*_c) are independent of (k^f). Intuitively, payments to foreign capital operating in the home country constitute a direct income transfer from the home to the foreign country. Therefore, the income loss of the home country exactly outweighs the income benefit of the foreign country, and as such it does not affect the maximization of their joint welfare.

In the present context of simultaneous cooperative choice of lump-sum (i.e., $\hat{S}_g = \hat{S}^*_{g^*} = 0$) and pollution taxes, equations (26) and (27) reduce to $t_c = P_g$ and $t^*_c = P^*_{g^*}$. However, if lump-sum taxes were not chosen cooperatively it is possible that $t_c \gtrless P_g$ and/or $t^*_c \gtrless P^*_{g^*}$. For example, if each country chooses the level of its lump-sum taxes non-cooperatively in order to maximize its own welfare, then while the level of public pollution abatement in each country is locally optimally provided from its own perspective, from the trading block's point of view, due to the assumed cross-border pollution externality, there is global under-provision in both countries ($\hat{S}_g = \Theta^* E^*_{r^*} > 0$, and $\hat{S}^*_g = \Theta E_r > 0$). In this case, $t_c > P_g$ and $t^*_c > P^*_{g^*}$.

Proposition 2 *Consider a two-country trading block with perfect capital mobility, and cross-border pollution between them. Part of pollution abatement is carried out by the public sector financed by means of lump-sum and pollution taxes. The first-best policy choice, maximizing the countries joint welfare, entails their cooperation in choosing both their respective lump-sum and pollution taxes.*

Note that cross-border pollution, not intra-block capital mobility, is the feature of the model mandating that the two countries choose cooperatively both lump-sum and pollution taxes in attaining the first-best policy choice. In the absence of cross-border pollution, the cooperative choice of pollution taxes alone suffices for attaining the first-best policy choice.

4.2 Optimal Pollution Taxes when Countries are Stackelberg Followers

Before proceeding on to examining the standard non-cooperative (Nash) regime, we present a case where each country acts as a Stackelberg follower. In particular, we assume that the foreign country chooses its tax level, (t^*), first and we examine how the home country reacts optimally in choosing its optimal pollution tax level (t). A similar exercise is pursued for the foreign country. In doing so we set $(du/dt) = 0$ and $(du^*/dt^*) = 0$ in equations (18) and (20) to obtain the optimal pollution taxes (t) and (t^*) in this case as follows:

$$t = P_g + \frac{-S_g H R_t P^*_{g^*} + \Theta R_{tK} R^*_{t^*K^*} P_g E_r (P^*_{g^*} - t^*) - k^f R_{tK} R^*_{K^*K^*} P_g P^*_{g^*}}{E_r P^*_{g^*}(H R_{tt} - R^2_{tK})} \tag{28}$$

$$t^* = P^*_{g^*} + \frac{-S^*_{g^*} H R^*_{t^*} P_g + \Theta^* R_{tK} R^*_{t^*K^*} P^*_{g^*} E^*_{r^*}(P_g - t) + k^f R^*_{t^*K^*} R_{KK} P_g P^*_{g^*}}{E^*_{r^*} P_g (H R^*_{t^*t^*} - R^{*2}_{t^*K^*})}. \tag{29}$$

Equations (28) and (29) represent each country's policy reaction function. The following proposition highlights several important features of this regime:

Proposition 3 *Under the conditions of the model, and assuming that one country acts as a Stackelberg leader and the other as a Stackelberg follower, then for the Stackelberg follower:*

1. *the optimal pollution tax is equal to the unit price of the public pollution abatement when the latter is locally optimally provided and there is no intra-block capital mobility.*
2. *the presence of intra-block capital mobility increases the optimal pollution tax for the net capital importing country and decreases it for the net capital exporting country in the absence of transboundary pollution, and*
3. *the presence of intra-block capital mobility decreases the optimal pollution tax in the presence of transboundary pollution, when initially $k^f = 0$ and the other country's pollution tax is smaller than the unit price of public pollution abatement.*

The first result of Proposition 3 states that in the absence of the cross-border pollution externality ($\Theta = 0$) and of foreign capital operating in the home country ($k^f = 0$), then $t = P_g$ in the home country, and $t^* = P^*_{g^*}$ in the foreign country. For the second result, the existence of intra-block capital mobility raises pollution in the home, capital-importing, country, and reduces it in the foreign, capital-exporting, country. Then, in the absence of cross-border pollution and since the pollution tax choice of the Stackelberg leader is given, such capital flows lead to a higher pollution tax in the capital-importing country, and to a lower pollution tax in the capital-exporting one.

For the third result, that in the presence of transboundary pollution (i.e., $\Theta > 0$ and $\Theta^* > 0$) a small intra-block capital mobility (i.e., k^f is close to 0) reduces the pollution tax (t) in the home country when $t^* < P^*_{g^*}$, the intuition is as follows. The only effect of capital mobility on welfare, in this case, is through its effect on foreign pollution, $z^* - g^*$. An increase in t reduces R_K which causes capital to move from the home to the foreign country. The increase in capital in the foreign country affects both z^* and g^*. The level of pollution z^* rises because the increase in capital increases the production of the capital-intensive polluting good. The increase in pollution, however, increases the tax receipts of the foreign government and therefore the provision of public pollution abatement, g^*.

Since $t^* < P^*_{g^*}$ the former outweighs the latter and thus the increase in t leads to an increase in $z^* - g^*$, and through transboundadry pollution this increase in r reduces u leading to a decrease in the optimal pollution tax, t. Similarly, a small intra-block capital mobility reduces (t^*) in the foreign country, when in the home country $t < P_g$.

4.3 Nash Equilibrium Lump-sum and Pollution Taxes

We know turn to derive the optimal Nash lump-sum and pollution taxes for the home and foreign countries and compare them to the benchmark cooperative case. The two countries choose these taxes simultaneously. In this non-cooperative game the only interactions between the two countries relevant to the analysis are those emanating from cross-border pollution and intra-block capital mobility.

4.3.1 Nash Lump-sum Taxes

Setting equations (16) and (17) equal to zero, we derive the Nash lump-sum taxes. The emerging equilibrium conditions require that Nash lump-sum taxes are chosen such that for the home country $E_r = P_g$ and for the foreign country such that $E^*_{r^*} = P^*_{g^*}$. These conditions constitute a dominant strategy for each country. That is, each country's choice of lump-sum taxes is independent of the other country's policy choice.

Comparing the Nash optimality conditions to those of the benchmark cooperative case we derive the following Proposition.

Proposition 4 *Under the conditions of the model Nash lump-sum tax levels are lower than the corresponding cooperative levels.*

Proof. Consider the case of the home country. Since P_g is constant and the same in both regimes, from equations (24), (25), and the discussion above it must hold that $E^N_r = E^C_r + \Theta^* E^{*C}_r$.[21] This implies that $E^N_r > E^C_r$. Given that the expenditure function is assumed strictly convex in (r), we get that $r^N > r^C$. As shown by the comparative statics in the Appendix, an increase in (T) does not affect the level of gross pollution (z), therefore $r^N > r^C$ implies that $g^N < g^C$. As a result we get that $T^N < T^C$. Similar reasoning yields $T^{*N} < T^{*C}$ for the foreign country. ■

[21] The superscripts (N) and (C) denote the variables evaluated at the Nash and the cooperative equilibrium, respectively.

Intuitively, the individual governments in setting their lump-sum taxes, do not account for the fact that because of cross-border pollution (i.e., a negative externality), the other country is willing to incur some of the cost of pollution abatement in the first country. Therefore, individual governments by not internalizing this externality set their Nash lump-sum taxes too low. In contrast, in the cooperative case the two countries accounting for this externality apply the relevant Samuelsonian rule for the trading-block optimal provision of the public pollution abatement.

4.3.2 Nash Pollution Taxes

To derive the Nash pollution taxes for the two countries we set $\frac{du}{dt} = 0$ and $\frac{du^*}{dt^*} = 0$. These reaction functions are given by equations (28) and (29). In contrast to the cooperative case, payments to foreign capital operating in the home country affect the size of each country's Nash pollution tax level.

Given that the structure of the game is such that lump-sum taxes are optimally chosen (i.e., $S_g = S^*_{g^*} = 0$), solving simultaneously equations (28) and (29) gives the following expressions for each country's Nash pollution taxes.[22]

$$t_N = P_g - k^f R_{tK} P_g^2 P^*_{g^*} [E^*_{r^*} R^*_{K^*K^*} (HR^*_{t^*t^*} - R^{*2}_{t^*K^*}) + \Theta R_{KK} R^{*2}_{t^*K^*} E_r] / \Delta_N \tag{30}$$

$$t^*_N = P^*_g + k^f R^*_{t^*K^*} P^{*2}_{g^*} P_g [E_r R_{KK} (HR_{tt} - R^2_{tK}) + \Theta^* R^*_{K^*K^*} R^2_{tK} E^*_{r^*}] / \Delta_N \tag{31}$$

where $\Delta_N = E_r E^*_{r^*} P_g P^*_{g^*} [(HR_{tt} - R^2_{tK})(HR^*_{t^*t^*} - R^{*2}_{t^*K^*}) - \Theta\Theta^* R^2_{tK} R^{*2}_{t^*K^*}]$ and is positive. From equations (30) and (31) we note that when lump-sum taxes are optimally chosen, then the effect of pollution taxes on payments to foreign capital operating in the home country constitute the only difference between the Nash and cooperative cases.

Observing the above expressions we note that in general the Nash pollution taxes can be greater or smaller than the unit cost of the public pollution abatement, as opposed to the benchmark case of cooperative choice of both instruments. We resolve some of this ambiguity by stating the following Proposition, which considers some special cases in the context of the present model.

Proposition 5 *Under the conditions of the model*

1. *if* $\Theta = 0$, *then* $t_N > t_c = P_g$.

[22] The general expressions for the Nash pollution taxes when lump-sum taxes are not chosen optimally are given in the Appendix.

2. *if* $\Theta^* = 0$, *then* $t_N^* < t_c^* = P_{g^*}^*$.

3. *if the two countries are symmetric in the sense that* $E_r = E_{r^*}^*$ *and* $R_{KK} = R_{K^*K^*}^*$, *then* $t_N > t_c$ *and* $t_N^* < t_c^*$.

4. *if initially* $k^f = 0$, *then* $t_N = t_c$ *and* $t_N^* = t_c^*$.

The proof of Proposition (5) follows from equations (30) and (31). Intuitively, the first two cases of Proposition (5) are directly derived from the assumption that home is the capital-importing and foreign is the capital-exporting country, and from the assumption that pollution is a capital intensive good in both countries. That is, the inflow of capital in the home country raises pollution, thus leading to a higher domestic Nash pollution tax level. The reverse holds for the foreign capital-exporting country. The intuition of the third case is as follows. Payments to foreign capital operating in the home country reduce real income, and thus lower the domestic households marginal willingness to pay for pollution abatement (i.e., $E_{ru} > 0$). As a result, at a constant pollution tax (t), net pollution generated at home (i.e., $z - g$) rises. At the same time, the opposite holds in the foreign country, i.e., $z^* - g^*$ falls. If the two countries are symmetric, and since $\Theta < 1$ and $\Theta^* < 1$, then net pollution ($r = z - g + \Theta(z^* - g^*)$) in the home country rises, and net pollution ($r^* = z^* - g^* + \Theta^*(z - g)$) in the foreign country falls. Therefore, we get that in the home country $t_N > t_c$, and in the foreign country $t_N^* < t_c^*$. Finally, in the last case where initially $k^f = 0$, there are no payments to foreign capital operating at home, and thus the cooperative and Nash pollution tax levels are the same. It is important, however, to note that if the two countries cooperate only in choosing their pollution taxes while lump-sum taxes are chosen non-cooperatively (Nash taxes), then $t_c > P_g$ and $t_c^* > P_{g^*}^*$ and if $k^f = 0$ then $t_N < t_c$ and $t_N^* < t_c^*$.

5 Capital Mobility and the Effect of Pollution Taxes on net Pollution

In what follows we examine how, ceteris paribus, intra-block capital mobility alters the effectiveness of pollution taxes in reducing net pollution. The analysis utilizes different initial conditions according to whether or not the two countries act cooperatively in choosing optimally their policy instruments (i.e., lump-sum and/or pollution taxes). Namely, we examine how capital mobility affects the impact of an increase in pollution taxes on net pollution (dr/dt) in each of the three cases in Section 4, that is, when (i) the two countries choose their policies cooperatively, (ii) one country acts as a Stackelberg follower and, (iii) both countries choose their policies non-cooperatively (Nash).

Consider the case of no intra-block capital mobility. Then, in all three cases above, when lump-sum taxes are optimally chosen, cooperatively in the cooperative case (i.e., $\hat{S}_g = \hat{S}^*_{g^*} = 0$) and non-cooperatively in the other two cases (i.e., $S_g = S^*_{g^*} = 0$), the optimal pollution tax equals the unit price of the public pollution abatement in both countries. This is easily observed from equations (26) and (27) in the case of the cooperative equilibrium, from equations (28) and (29) in the case where one country acts as a Stackelberg follower, and finally from equations (30) and (31) in the case of non-cooperative Nash equilibrium. Moreover, equation (13), and its counterpart for the foreign country (i.e., dr^*/dt^*) indicate that raising the pollution tax, unambiguously reduces local net pollution.[23] Note that the first two right-hand-side terms in the reduced form of equation (13), are due to the intra-block capital mobility.

Assuming the existence of intra-block capital mobility, we first consider the case where the two countries choose cooperatively both their lump-sum and pollution taxes in order to maximize their joint welfare. In this case, the cooperative pollution taxes equal the prices of public pollution abatement in each country and thus the effect of pollution taxes on net pollution is not affected by the presence of capital mobility when evaluated at the cooperative equilibrium. If, however, the two countries cooperate in their choice of pollution taxes but choose lump-sum taxes non-cooperatively, so as to each maximize its own welfare, then the effect of the presence of capital mobility is ambiguous. For zero or small Θ, the presence of capital mobility reduces the effectiveness of the increase in pollution taxes on net pollution, dr/dt.[24] Similarly, for small Θ^*, the presence of capital mobility increases dr^*/dt^*.

Next, consider the case where the home country acts as a Stackelberg follower. Combining equation (28) and equation (13), we can conclude that the presence of capital mobility reduces the effectiveness of the increase in the capital-importing country's pollution tax on its net pollution, (dr/dt) when Θ is small, or zero. Note, that the overall effect may even become positive. The opposite is true for the capital-exporting country.

[23] It is easily shown that when lump-sum taxes are optimally chosen, and in the absence of intra-block capital mobility, $(dr/dt) = -\Delta^{-1} P^*_{g^*} R_t < 0$, and similarly, $(dr/dt) = -\Delta^{-1} P_g R^*_{t^*} < 0$.

[24] In other words it increases dr/dt. The more negative dr/dt is the more effective t is in reducing net pollution.

In all other cases, the effect is ambiguous.

Finally, we examine how the presence of capital mobility affects the impact of an increase in the home pollution tax on its net pollution evaluated at Nash equilibrium. The following Proposition summarizes the results:

Proposition 6 *Within the assumptions of the model, the presence of capital mobility decreases (increases) the effectiveness of an increase in the pollution tax on net pollution evaluated at Nash*[25] *for the capital importing (exporting) country if i)* $\Theta = 0$ $(\Theta^* = 0)$ *and* $\Theta^* \geq 0$ $(\Theta \geq 0)$ *and ii) when* $\Theta > 0$ *and* $\Theta^* > 0$ *and both countries are symmetric.*

Intuitively, when $\Theta = 0$ the residents of the home country are only affected by changes in, $z - g$. Capital mobility affects both z and g. The increase in t leads to an outflow of capital from the home to the foreign country, which in turn lowers z. On the other hand the effect on g is negative since the capital outflow reduces pollution and thus pollution tax revenue. At Nash $t > P_g$ and thus the effect on g is smaller than that on z, and thus $z - g$ is reduced. In the presence of transboundary pollution ($\Theta > 0$ and $\Theta^* > 0$) the same result holds if the two countries are symmetric. The intuition is the same as that following Proposition (5). It is important to note that if initially $k^f = 0$, then the presence of capital mobility does not affect the impact of the pollution tax on net pollution.

6 Conclusion

The dawn of the new century has presented the world economy with two eminent challenges. The first is the rapidly growing interdependence amongst national economies through the process of global or regional economic integration. The second challenge is the increasingly higher value placed by the international community on the protection and preservation of the global natural environment. As a result, there is an emerging need for international cooperation in the design and implementation of economic policies that minimize the local and global environmental damages of this increasing economic integration. These two challenges have triggered a relatively modern economic literature on the so-called "trade vs environment" debate. This literature in formalizing and examining this debate has identified cross-border pollution externalities and international capital

[25] Nash equilibrium refers to the case where the two countries apply their Nash lump-sum taxes and their Nash pollution taxes simultaneously.

mobility as key factors affecting domestic trade and environmental policies and thus emphasizes the need for international coordination. While most of the literature assumes that pollution is abated solely by the private sector in response to emission taxes imposed by governments, a recent strand with less than a handful of theoretical contributions, has put forth a third relevant feature of this problem. That of the simultaneous undertaking of pollution abatement by private and public sectors, and of accounting for the means of financing public sector abatement activity. Yet, to the best of our knowledge, no study of this literature has attempted to incorporate all three analytical features, that is, transboundary pollution, simultaneous provision of private and public sector pollution abatement, and capital mobility.

The present paper undertakes this task and highlights the interaction among these three features regarding the design of environmental policies in today's highly integrated global economy. To this end, we present a a two-country trading block model with cross border pollution, free trade in goods and perfect capital mobility within the trading block. The trade in goods between the trading block and the rest of the world is free, while the mobility of capital is restricted. Pollution, a by-product of production, adversely affects welfare and it is abated by the private and public sectors in both countries. The government uses revenue collected from pollution and lump-sum taxes to finance public pollution abatement.

Within this framework, the first-best policy is achieved when both countries choose both tax instruments cooperatively. In this case, the optimal pollution tax in each country equals the unit cost of public pollution abatement and the optimal lump-sum tax in each country is the one that equalizes the unit cost of public pollution abatement in that country with the global damage caused by a unit of pollution generated by that country. If, however, each country chooses only the pollution taxes cooperatively, while lump-sum taxes are chosen non-cooperatively (i.e., to maximize its own welfare), then from the trading block's perspective, due to cross-border pollution, there is under-provision of public pollution abatement, and the cooperative pollution tax is greater than the unit cost of public pollution abatement.

When each country acts non-cooperatively, in order to maximize its own welfare, then i) the non-cooperative lump-sum taxes are lower than the cooperative ones, ii) the cooperative and non-cooperative pollution taxes are equal only in the case where initially the net capital stock of one country into the other is zero, iii) if countries are symmetric in the sense described by proposition 5, the Nash pollution tax is greater than its cooperative level for the capital importing country (the opposite is true for the capital-exporting country), and iv) in general, if no foreign pollution is transmitted in the capital importing country, then its Nash pollution tax is higher than the cooperative one and similarly if no foreign pollution is transmitted into the capital exporting country, then its Nash pollution tax is lower than the cooperative one.

The presence of intra-block capital mobility does not alter the effectiveness of pollution taxes in reducing net pollution when each country chooses both tax instruments cooperatively. If, however, each country chooses its pollution tax cooperatively and the lump-sum tax non-cooperatively, then the presence of capital mobility reduces the effectiveness of the pollution tax on net pollution for each country. When both countries behave non-cooperatively, then the presence of capital mobility lowers (raises) the effectiveness of an increase in the pollution tax on net pollution for the capital-importing (exporting) country, if there is no flow of foreign pollution in that country or when there is cross border pollution but the countries are symmetric.

Appendix

$$\begin{bmatrix} 1 & 0 & -E_r & -\Theta E_r & -E_r(R_{tK} - \Theta R^*_{t^*K^*}) + k^f R_{KK} \\ 0 & 1 & -\Theta^* E^*_{r^*} & -E^*_{r^*} & E^*_{r^*}(R^*_{t^*K^*} - \Theta^* R_{tK}) - k^f R_{KK} \\ 0 & 0 & P_g & 0 & tR_{tK} \\ 0 & 0 & 0 & P^*_{g^*} & -t^* R^*_{t^*K^*} \\ 0 & 0 & 0 & 0 & H \end{bmatrix} \begin{bmatrix} du \\ du^* \\ dg \\ dg^* \\ dK \end{bmatrix} =$$

$$\begin{bmatrix} E_r R_{tt} + R_t - k^f R_{tK} \\ \Theta^* E^*_{r^*} R_{tt} + k^f R_{tK} \\ -R_t - tR_{tt} \\ 0 \\ -R_{tK} \end{bmatrix} dt + \begin{bmatrix} \Theta E_r R^*_{t^*t^*} \\ E^*_{r^*} R^*_{t^*t^*} + R^*_{t^*} \\ 0 \\ -R^*_{t^*} - t^* R^*_{t^*t^*} \\ -R^*_{t^*K^*} \end{bmatrix} dt^*$$

$$+ \begin{bmatrix} -1 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} dT + \begin{bmatrix} 0 \\ -1 \\ 0 \\ 1 \\ 0 \end{bmatrix} dT^*$$

$t_N = P_g + \{E^*_{r^*} P_g (H R^*_{t^*t^*} - R^{*2}_{t^*K^*})(-S_g H R_t P^*_{g^*} - k^f R_{tK} R^*_{K^*K^*} P_g P^*_{g^*})$
$-\Theta R_{tK} R^*_{t^*K^*} P_g E_r (-S^*_{g^*} H R^*_{t^*} P_g + k^f R_{KK} R^*_{t^*K^*} P_g P^*_{g^*})\}/\Delta_N$
$t^*_N = P^*_{g^*} + \{E_r P^*_{g^*} (H R_{tt} - R^2_{tK})(-S^*_{g^*} H R^*_{t^*} P_g + k^f R^*_{t^*K^*} R_{KK} P_g P^*_{g^*})$
$-\Theta^* R_{tK} R^*_{t^*K^*} P^*_{g^*} E^*_{r^*} (-S_g H R_t P^*_{g^*} - k^f R^*_{K^*K^*} R_{tK} P_g P^*_{g^*})\}/\Delta_N$
$\Delta \frac{dr}{dt^*} = -P^*_{g^*} R_{tK} R^*_{t^*K^*} (P_g - t) - \Theta P_g (H R^*_{t^*t^*} - R^{*2}_{t^*K^*})(P^*_{g^*} - t^*) + \Theta H P_g R^*_{t^*}$
$\Delta \frac{dr^*}{dt^*} = -P_g (H R^*_{t^*t^*} - R^{*2}_{t^*K^*})(P^*_{g^*} - t^*) - \Theta^* R_{tK} R^*_{t^*K^*} P^*_{g^*} (P_g - t) + H P_g R^*_{t^*}$

$\frac{du}{d\Theta} = -E_r(-R^*_{t^*} - g^*)$	$\frac{dK}{d\Theta^*} = 0$	$\frac{dg^*}{d\Theta} = 0$
$\frac{du}{d\Theta^*} = 0$	$\Delta \frac{dg}{dt^*} = -P^*_{g^*} t R_{tK} R^*_{t^*K^*}$	$\frac{dg^*}{d\Theta^*} = 0$
$\frac{du^*}{d\Theta} = 0$	$\Delta \frac{dg}{dT} = H P^*_{g^*}$	$\frac{dr}{dT} = \frac{-1}{P_g}$
$\frac{du^*}{d\Theta^*} = -E^*_{r^*}(-R_t - g)$	$\frac{dg}{dT^*} = 0$	$\frac{dr}{dT^*} = \frac{-\Theta}{P^*_{g^*}}$
$\frac{dK}{dt} = \frac{-R_{tK}}{H}$	$\frac{dg}{d\Theta} = 0$	$\frac{dr}{d\Theta} = -R^*_{t^*} - g^*$
$\frac{dK}{dt^*} = \frac{R^*_{t^*K^*}}{H}$	$\frac{dg}{d\Theta^*} = 0$	$\frac{dr}{d\Theta^*} = 0$
$\frac{dK}{dT} = 0$	$\Delta \frac{dg^*}{dt^*} = P_g t^* R^{*2}_{t^*K^*} - H P_g (R^*_{t^*} + t^* R^*_{t^*t^*})$	$\frac{dr^*}{dT} = \frac{-\Theta^*}{P_g}$
$\frac{dK}{dT^*} = 0$	$\Delta \frac{dg^*}{dT} = 0$	$\frac{dr^*}{dT^*} = \frac{-1}{P^*_{g^*}}$
$\frac{dK}{d\Theta} = 0$	$\Delta \frac{dg^*}{dT^*} = H P_g$	$\frac{dr^*}{d\Theta} = 0$

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