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Abstract

We construct a two-good general equilibrium model of international trade for two small open economies where pollution from production is transmitted across borders. Governments in both countries impose emission taxes non-cooperatively. Within this framework, we examine the effect of trade liberalization and of changes in the perception of cross-border pollution on Nash emission taxes, emission levels, and welfare.

Key Words: Cross-border pollution, Emission taxes, Terms of trade, Trade liberalization, Welfare.
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1 Introduction

More than ever before, a dominant issue in current public policy debates among nations is that of international externalities associated with pollution generated in countries. This negative externality is allegedly exacerbated with the liberalization of international economic activities (*e.g.*, freer international mobility of goods and capital) feverishly pursued nowadays by numerous countries and international institutions.[1] In the light of such perceived environmental degradation emanating from expanded economic activities, environmentally conscious political and social groups have been staging fierce world-wide reactions against international negotiations (*e.g.*, the summits of WTO in Seattle, 2000, of IMF in Prague, 2001, and of the G-8 group in Geneva, 2001) promoting these objectives.

Accounting for such growing real world concerns, a sizable literature on the economics of international trade and cross-border pollution has, and is being, developed. A strand of this literature analyzes the implications of cross-border pollution and/or examines the welfare effects of selected pollution abatement (trade and environmental) policies (see, for example, Markusen, 1975; Copeland, 1994, 1996; Ludema and Wooton, 1994, 1997; Beghin *et al.*, 1997; Hatzipanayotou *et al.*, 2002, 2004).

There is now a small theoretical literature that examines the effect of international trade on pollution. For example, Rauscher (2001) examines whether it is optimal to employ a policy of 'ecological dumping' in the presence of terms of trade considerations. Copeland and Taylor (2003) which synthesizes their earlier papers, examine the effect of trade liberalization on welfare in, and emission by, a small open economy which has optimal environment policies in place. They find that when the country adjusts its optimal policies in response to trade liberalization, more trade increases welfare but can, under certain circumstances, increase pollution. They also consider a model of two large countries to examine the economic logic

[1]See, for example, Copeland and Taylor (2003) for a discussion of the issues.

behind pollution havens. They investigate, *inter alia*, if trade driven by environmental policy differences is bad for the environment and find that it is not necessarily so.

In this paper we develop a general equilibrium model for two small open economies with two-way cross-border pollution. Within this framework, we first characterize, in section 3, the non-cooperative optimal values for the emission tax rates. In section 4 we examine the effects of a reduction in trade costs, interpreted as an exogenous terms of trade shock or trade liberalization, on Nash equilibrium emissions tax rates, net pollution and welfare in the two countries. In section 5 we analyze how, changes in the perception about cross-border pollution affect Nash equilibrium emissions tax rates and national welfare in the two countries. Finally, some concluding remarks are offered in section 6.

2 The Theoretical Framework

We consider a general equilibrium model with two countries – called the home country and the foreign country – where pollution as a by-product of production is generated in both countries, and it is transmitted across national borders. For most part, we consider cross-border pollution as a two-way cross-country externality, although we shall consider a special case when it is one-way.

The two countries produce, under perfectly competitive conditions, two goods – good 1 and good 2 – which are freely traded in world markets. Good 1 is the *numeraire* commodity. We assume that both economies are small in the world commodity markets so that the international (relative) price of the non-mumeraire good 2 is exogenous.[2] Factors of production are internationally immobile and inelastically supplied. Factor markets in both

[2]Our model can depict, *inter alia*, the case of two countries in the European Union, affected by each other's (bilateral) cross-border pollution, with free trade between them and international commodity prices constant and equal to those in the rest of the world. This analytical simplification facilitates the objective of our analysis which is to examine environmental (*e.g.*, cross-border pollution) rather than international trade issues. It is to be noted that countries in the European Union are part of a much bigger world trading system. Therefore, the assumption that these countries do not have any market power in trade may not be very unrealistic.

countries are perfectly competitive. Producers in the two countries abate some of the pollution they generate in response to government imposed emission taxes at the rate t and t^* respectively.[3] Let e and e^* denote the level of pollution emission in the two countries.

For simplicity, we shall assume that only one of the two goods is polluting.[4] Which is the polluting good would depend on the nature of the goods and the type of pollutant we consider. For example, if the home country is a developing country which typically exports agricultural goods and the pollutant is nitrates in the water supply, then the import-competing sector is the pollutant. If, on the other hand, the pollutant is industrial waste, then the exportable sector is possibly the pollutant. We shall leave the assumption open for the time being.

We proceed now to develop the model for the home country; the model of the foreign country follows analogously. The country's maximum value of production is denoted by the gross domestic product, or revenue function, $R(p, t, v)$, defined as:

$$R(p, t, v) = \max_{x_1, x_2, e} \{x_1 + px_2 - te : (x_1, x_2, e) \in T(v)\},$$

where p is the is the world price of the non-numeraire good, $T(v)$ is the country's aggregate technology set,[5] x_1 and x_2 are the outputs of good 1 and good 2 respectively, v is the vector of endowments, e is the amount of pollution emission and t is the emission tax rate. Since total endowments of all factors of production, v, are exogenously given, for notational simplicity, it can be suppressed and the revenue function can be written simply as $R(p, t)$. Its partial derivative with respect to p (*i.e.*, R_p) denotes the supply function of the non-numeraire good 2. It is also known (*e.g.*, see Copeland, 1994, and Turunen-Red and Woodland, 2004) that its partial derivative with respect to t multiplied by -1 is the amount of pollution emissions by the private sector, *i.e.*,

$$e = -R_t(p, t). \tag{1}$$

[3] The variables in the foreign country are marked with asterisks.
[4] For simplicity, we consider only one type of pollution.
[5] It includes abatement technology in addition to production technology.

Analogously, for the foreign country we have

$$e^* = -R^*_{t^*}(p, t^*) \tag{2}$$

The revenue function is strictly convex in the emission tax rate (*i.e.*, $R_{tt} > 0$). This property indicates that an increase in the emission tax rate lowers the amount of pollution emission by the private sector. Moreover, if good 2 is the polluting one, a higher emissions tax rate (t) reduces the level of its production, *i.e.*, $R_{pt} < 0$. If, on the other hand, good 1 is the polluting one, we shall have $R_{pt} > 0$. Since we do not make any presumption on the pattern of trade, without any loss of generality, we assume, unless stated otherwise, that the non-numeraire good is the polluting good in both countries. This is formally stated in the following assumption.

ASSUMPTION **1** $\quad R_{tp} < 0 \quad \textit{and} \quad R^*_{t^*p} < 0.$

Turning to the demand side of the home country, utility, u, as previously noted is adversely affected by both local pollution, e, and by foreign pollution, e^* transmitted across borders. Denoting by θ the spill-over parameter, welfare in the home country is adversely affected by $z = e + \theta e^*$. It is to be noted that consumers often do not realize the full extent of cross-border pollution and thus the parameter θ is best described as a 'perception' parameter. That is, there is some amount of cross-border pollution into the country, but its residents perception regarding the actual extent of this cross-border pollution, and thus of total pollution in the country, is different than what actually is the case. A rise in the value θ may be interpreted as an increase in the perception about cross-border pollution.[6]

Let $E(p, z, u)$ be the expenditure function which gives minimum expenditure required by a representative consumer to achieve a given level of utility u given commodity (consumers') price p and aggregate level of pollution z. The partial derivative of the expenditure

[6]The perceived rate of cross border pollution θ can be greater, less, or equal to the actual rate of cross border pollution.

function with respect to u, E_u, gives the reciprocal of marginal utility of income, and that with respect to p, E_p, gives the compensated demand function of the non-numeraire good. Since pollution is a public bad, the partial derivative of the expenditure function with respect to z, E_z, is positive and denotes the households' *marginal willingness to pay for a reduction in pollution* (*e.g.*, see Chao and Yu, 1999). The expenditure function is also strictly convex in z, *i.e.*, $E_{zz} > 0$.[7] This property implies that a higher level of pollution raises the households' marginal willingness to pay for its reduction. Moreover, we also make the natural assumption that $E_{zu} > 0$, that is, a higher level of real income increases the households' marginal willingness to pay for pollution abatement. Finally, $E_{pz} \lesseqgtr 0$, depending on whether cleaner environment and good 2 are complements (*i.e.*, $E_{pz} < 0$) or substitutes (*i.e.*, $E_{pz} > 0$) or independent in consumption (i.e., $E_{pz} = 0$). Note that an increase in z increases expenditure for a given utility level, *i.e.*, $E_z > 0$. This increase in expenditure has to involve an increase in consumption of at least one of the two goods. For the additive direct utility function of the form: $u(c_1, c_2, z) = v(c_1, c_2) - f(z)$, where c_i is the consumption of good i $(i = 1, 2)$, the expenditure function takes the form $E(p, u + f(z))$ and thus cleaner environment and the non-numeraire good are not complements ($E_{pz} \geq 0$). In addition, if the direct utility function is quasi-linear, *i.e.*, $v(c_1, c_2) = \bar{v}(c_2) + \lambda c_1$ where λ is a constant parameter, cleaner environment and the non-numeraire good are independent in consumption, *i.e.*, $E_{pz} = 0$, and all the adjustments of a change in z (at a given utility level) fall on the numeraire good.[8] One can also think of a situation where a higher level of pollution induces people to consume less of the polluting good and in this case cleaner environment and polluting (the non-numeraire) good are complements, *i.e.*, $E_{pz} < 0$. This will be the case, for example, when the direct utility is of the form $u(c_1, c_2, z) = c_2^{\alpha} z^{-\beta} + \lambda c_1$ where $\alpha < 1$ and $\beta > 0$.[9]

The budget constraint for a representative consumer requires that total expenditure

[7] E_{zz} is positive irrespective of the source of pollution.

[8] See Wilson (1991)and Lahiri and Raimondos-Møller (1998) for a discussion on the separability between public and private goods.

[9] Copeland and Taylor (2003) use a direct utility function that is additive in z, and thus in their case $E_{pz} \geq 0$ always.

$E(p, z, u)$ must equal factor income from the production of the two traded goods $R(p, t)$ plus the emission tax revenue (te) that the government returns to the representative consumer in a lump-sum fashion. That is,

$$E(p, z, u) = R(p, t) + te. \tag{3}$$

Analogously, for the foreign country we have

$$E^*(p, z^*, u^*) = R^*(p, t^*) + t^*e^*, \tag{4}$$

where $z^* = e^* + \theta^* e$ and θ^* is the spill-over or the perception of cross-border pollution parameter for the foreign country. For the case where we treat cross-border pollution as a one-way cross-country externality we have either $\theta^* > 0$ and $\theta = 0$ or $\theta^* = 0$ and $\theta > 0$.

Imports of the non-numeraire good in the two countries are given by $M = E_p - R_p$ and $M^* = E_p^* - R_p^*$ respectively.

Equations (1)-(4) constitute a system of four equations in four unknowns, namely u, u^*, e and e^*. The model contains two policy parameters, one for each country, and these are the emission tax rates (t, t^*).

We conclude this section by examining how the policy parameters affect the endogenous variable of our model. Differentiating equations (1) to (4) we obtain the changes in the level of the home country and the foreign country's welfare as follows:

$$E_u \; du = A_p \; dp + A_t \; dt + A_{t^*} \; dt^* + A_\theta d\theta, \tag{5}$$

$$E^*_{u*} \; du^* = B_p \; dp + B_{t^*} \; dt^* + B_t \; dt + B_{\theta^*} d\theta^*, \tag{6}$$

where

$$\begin{aligned} A_p &= (E_z - t)R_{tp} - M + \theta R^*_{t^*p} E_z, \quad A_t = R_{tt}(E_z - t) \\ A_{t^*} &= \theta E_z R^*_{t^*t^*}, \; A_\theta = E_z R^*_{t^*}, \; B_p = (E^*_{z^*} - t^*)R^*_{t^*p} - M^* + \theta^* R_{tp} E^*_{z^*}, \\ B_{t^*} &= R^*_{t^*t^*}(E^*_{z^*} - t^*), \quad B_t = \theta^* E^*_{z^*} R_{tt}, \; B_{\theta^*} = E^*_{z^*} R_t. \end{aligned}$$

Equation (5) indicates that there are three effects of p on u: (i) the well-known terms-of-trade effect $(-Mdp)$: an improvement in the term of trade increases welfare, (ii) an effect via changes in tax revenue $(-tR_{tp})$; and (iii) an effect via changes in disutility of pollution from changes in pollution in the home country (E_zR_{tp}) and that from cross-border pollution$(E_zR^*_{t^*p})$. If, for example, the home country is an importer of the non-numeraire good $(M > 0)$, an improvement in its terms of trade $(dp < 0)$ increases welfare, *i.e.* the first effect is positive. Since the non-numeraire good is the polluting one (assumption 1), we have $R_{tp} < 0$ and then the second effect is positive and the third effect negative. In this case, a sufficient condition for the net effect of an improvement in terms of trade to be positive is that pollution is socially under or optimally taxed, i.e., $E_z \geq t$.

An increase in the own tax rate t entails a positive impact on welfare if and only if (at a given p) $E_z > t$. The third term in equation (5) $(A_{t^*}dt^*)$ captures the international tax externality. It states that an increase in one country's emission tax rate unambiguously raises the welfare of the other country by reducing cross-border pollution. Finally, the last term in (5) $(A_\theta d\theta)$ simply states that an increase in the perception of cross-border pollution, *ceteris paribus*, increases disutility. Equation (6) can similarly be explained. Note that if a country does not perceive to suffer from cross-border pollution, it is not affected by changes in emission tax in the other country.

3 The Nash Equilibrium

Having explained the welfare equations, we can now characterize the non-cooperative Nash equilibrium levels of the policy instruments, *i.e.*, when the two countries choose respectively the levels of (t and t^*) simultaneously by maximizing their respective welfare, with each country treating the other's policy parameters as given. That is:

$$\frac{\partial u}{\partial t} = A_t = 0, \quad \frac{\partial u^*}{\partial t^*} = B_{t^*} = 0. \tag{7}$$

Since cross-border pollution externalities are not internalized, the optimality conditions give the well-known Pigouvian rule, *i.e.*, the tax rate in each country is equal to the marginal willingness to pay for pollution reduction:

$$E_z = t, \quad E^*_{z^*} = t^*. \tag{8}$$

However, since the two countries are related via cross-border pollution, the two equations in (8) *simultaneously* determine the Nash equilibrium values of the policy instruments in the two countries.

Differentiating the two equations in (7) and evaluating everything at the Nash equilibrium, we obtain:

$$A_{tt}dt + A_{tt^*}dt^* = -A_{tp}dp - A_{t\theta}d\theta, \tag{9}$$

$$B_{t^*t}dt + B_{t^*t^*}dt^* = -B_{t^*p}dp - B_{t^*\theta^*}d\theta^*, \tag{10}$$

where

$$\begin{aligned}
A_{tt} &= -R_{tt}(E_{zz}R_{tt}+1) < 0, \qquad A_{t\theta} = R^*_{t^*}R_{tt}\,(E_z/z)\,(-\epsilon_{zz}+\eta_{zu}),\\
A_{tt^*} &= \theta R^*_{t^*t^*}(-E_{zz}+E_u^{-1}E_zE_{zu})R_{tt} = \theta R_{tt}R^*_{t^*t^*}(E_z/z)(-\varepsilon_{zz}+\eta_{zu})\\
A_{tp} &= R_{tt}\left[E_{zp} - (R_{tp}+\theta R^*_{t^*p})E_{zz} + E_u^{-1}E_{zu}(\theta t R^*_{t^*p} - M)\right]\\
&= R_{tt}(E_{zp} - z^{-1}M\eta_{zu}) + R_{tt}(E_z/z)[\theta R^*_{t^*p}\eta_{zu} - (R_{tp}+\theta R^*_{t^*p})\epsilon_{zz}],
\end{aligned}$$

where $\varepsilon_{zz} = (z/E_z)E_{zz}$ is the home country's elasticity of marginal willingness to pay for pollution abatement with respect to pollution, and $\eta_{zu} = -(\partial(1/E_u)/\partial z)(zE_u) = zE_u^{-1}E_{zu}$ is the absolute value of the home country's elasticity of the marginal utility of income with respect to pollution. $B_{t^*t^*}$, B_{t^*t}, B_{t^*p}, and $B_{t^*\theta^*}$, and $B_{t^*\theta}$ are similarly defined. We use equations (9) and (10) to examine the impact of exogenous changes in the terms of trade and of changes in the perception of cross-border pollution on the Nash equilibrium emission tax rates (t and t^*). These results are an intermediate step in examining the effect of these parameters on welfare and pollution.

4 Globalization, pollution and welfare

The analysis in this section is an extension of Copeland and Taylor (2003, ch. 4) where they consider a *single* small open economy affected by its own pollution. We examine the effect of a change in the exogenous terms of trade on the Nash equilibrium tax rates in the two countries and on their welfare and emission levels. As pointed out by Copeland and Taylor (2003, ch.4), an improvement in the terms of trade can be equivalently interpreted as a decrease in trade costs of the iceberg type and thus can represent trade liberalization.

From equations (9) and (10) we obtain the effect of an exogenous terms of trade change on the Nash equilibrium tax rates as follows:

$$\Omega \cdot \frac{dt^N}{dp} = -A_{tp}B_{t^*t^*} + A_{tt^*}B_{t^*p} \tag{11}$$

$$\Omega \cdot \frac{dt^{*N}}{dp} = -A_{tt}B_{t^*p} + B_{t^*t}A_{tp}, \tag{12}$$

where, $\Omega = A_{tt}B_{t^*t^*} - A_{tt^*}B_{t^*t} > 0$ for the stability of the Nash equilibrium, and the superscript 'N' denotes the Nash equilibrium values of the policy instruments.

Observing equation (11) and (12) we note that the effect of an exogenous terms of trade shock on Nash equilibrium tax rates is in general ambiguous. However, for the general case, we can derive a set of sufficient conditions under which the above derivatives can be signed. Suppose that the following conditions are satisfied: (i) the non-numeraire good and cleaner environment are weak-complements in consumption,[10] *i.e.*, $E_{zp} \leq 0$, $E^*_{z^*p} \leq 0$, (ii) both countries import the non-numeraire good, *i.e.*, $M > 0$, $M^* > 0$, and (iii) the income effect on consumers' willingness to pay for reduced pollution is sufficiently high; in particular for home $\eta_{zu} > [1+(R_{tp}/(\theta R^*_{t^*p}))]\epsilon_{zz}$ and $\eta^*_{z^*u^*} > [1+(R^*_{t^*p}/\theta^* R_{tp})]\epsilon^*_{z^*z^*}$, then, since $R_{tp} < 0$, $R^*_{t^*p} < 0$, it can be shown that $A_{tp} < 0$, $B_{t^*p} < 0$, $A_{tt^*} > 0$ and $B_{t^*t} > 0$. More, we already know that $A_{tt} < 0$ and $B_{t^*t^*} < 0$. Therefore, under the conditions (i)-(iii) we have

[10] By weak-complements in consumption we mean that cleaner environment and good 2 are complements or independent in consumption.

$dt^N/dp < 0$ and $dt^{*N}/dp < 0$. That is, under these sufficient conditions, an improvement in the terms of trade of the two countries ($dp < 0$) *increases* the Nash equilibrium emission taxes.

The second term and a part of the first term in equations (11) and (12) appear because of the presence of cross-border pollution. Trade pattern is also important in signing dt^N/dp and dt^{*N}/dp as can be seen from the third term in the definitions of A_{tp} and B_{t^*p}, respectively; in fact, an improvement in the terms of trade would tend to increase t^N via this effect. However, the cross-border effect can, in theory, outweigh this effect. For example, in the case of dt^N/dp if $\eta_{zu} < \epsilon_{zz}$ and $\eta^*_{z^*u^*} < \epsilon^*_{z^*z^*}$ then it is possible that an improvement in terms of trade to reduce the levels of the Nash equilibrium emission taxes in the two countries.

In order to obtain simpler sufficient conditions to sign (11) and (12), we now consider two special cases. First, we consider the case of one-way cross-border pollution, *e.g.*, $\theta^* > 0$ and $\theta = 0$ (*i.e.*, the home country pollutes the foreign country while the later country does not pollute the home country). Then, equation (12) remains unchanged while equation (11) reduces to:

$$\Omega \frac{dt^N}{dp} = -A_{tp} B_{t^*t^*}, \tag{13}$$

where now $A_{tp} = E_{zp} - M\eta_{zu}/z - R_{tp}E_{zz}$. In this case, if η_{zu} is sufficiently large, an improvement in the country's term of trade unambiguously increases the Nash equilibrium emissions tax rate.

Second, we consider the case where the two countries are symmetric. In such a case, equation (9) reduces to:

$$\frac{dt^N}{dp} = -\frac{A_{tp}}{A_{tt} + A_{tt^*}}, \tag{14}$$

where $A_{tp} = E_{zp} - Mz^{-1}\eta_{zu} + (E_z/z)[\theta\eta_{zu} - (1+\theta)\epsilon_{zz}]R_{tp}$, and $A_{tt} + A_{tt^*}$ is negative for the stability of the Nash equilibrium. If the home country is an importer of the polluting good, *i.e.*, $M > 0$, then, since $R_{tp} < 0$, a sufficient condition for an improvement in the terms of trade, *i.e.*, $dp < 0$, to raise the Nash equilibrium emissions tax rate is once again that η_{zu} is sufficiently large. The reason why the size of η_{zu} is important is as follows. An improvement in the terms of trade increases real income, and this increase in income raises the willingness to pay for reduced pollution. The strength of the relationship between real income and the willingness to pay is given by the parameter η_{zu}: if this is sufficiently high the government is able to overcome conflicting demands on the emission tax rate and raise its Nash equilibrium value of it. The above result is stated formally in the following lemma.

Lemma 1 *Suppose that the two countries are symmetric and importers of the polluting good. Then an improvement in their terms of trade increases the Nash equilibrium tax rates if* η_{zu} *is sufficiently large.*

Having discussed how the Nash taxes may increase with an improvement in the terms of trade, we now examine the impact of an exogenous terms-of-trade change on welfare levels u and u^* and on pollution levels e and e^*. We do so by assuming that both countries are at the Nash equilibrium, i.e., the equations in (8) are satisfied, and by considering the cases where the two countries do, or do not, adjust optimally their Nash equilibrium emission tax rates, t^N and t^{*^N}, in response to terms of trade shocks. We pursue the analysis for the home country and analogously follows the analysis for the foreign country.

Differentiating equation (1) and using equations (5) and (8), for the home country we obtain:

$$\frac{du}{dp} = A_p + A_{t^*} \cdot \frac{dt^{*N}}{dp}, \tag{15}$$

$$\frac{de}{dp} = -R_{tp} - R_{tt} \cdot \frac{dt^N}{dp}, \tag{16}$$

where we evaluate these changes at Nash equilibrium. The first terms give the direct effects of a terms-of-trade shock. The second terms give the indirect effects via changes in the Nash equilibrium emission tax rates. It is to be noted that whereas the effect on utility depends on induced changes in the tax rate in the foreign country,[11] that on pollution emission depends on the induced changes in the home country's own tax rate. Note also that the second term in (15) ((16)) is absent when the foreign (home) country does not optimally adjust its Nash equilibrium tax rate.

First, we consider the case where the foreign country does not adjust optimally its Nash tax rate in response to a terms of trade change. Then, equation (15) reduces to $du/dp = A_p = -M + \theta E_z R^*_{t^*p}$. An improvement in its terms of trade increases its welfare if it imports the polluting good. This result holds regardless of whether or not this country responds to the terms-of-trade change by adjusting its Nash equilibrium tax rates. If $M > 0$ then $A_p < 0$ since it is assumed that the non-numeraire good is the polluting one ($R^*_{t^*p} < 0$, see assumption 1), implying that even in the presence of cross-border pollution a terms-of-trade improvement raises the home country's welfare (*i.e.*, $du/dp < 0$). Note that Copeland and Taylor (2003, ch. 4) show that for a small open economy, welfare unambiguously increases as a result of a terms-of-trade improvement if the initial tax rate is at the optimal level. In our case, in the presence of cross-border pollution, this result is reproduced with the additional constraint on the pattern of trade, i.e., both countries are importers of the polluting commodity. If the two countries are exporters of the the polluting good, then trade liberalization may reduce welfare as it increases the relative price of the polluting good in the other country, thus raising its production and cross-border pollution. Since cross-border pollution is not taken into account while setting Nash emission taxes, a terms-of-trade improvement can reduce welfare even when the emission taxes are at the Nash optimal levels.

When the home country does not respond to terms-of-trade shocks by adjusting its Nash equilibrium tax rate, equation (16) reduces to $de/dp = -R_{tp}$. Thus, if the home country is an importer of the polluting good, an improvement in its terms of trade ($dp < 0$) reduces the aggregate pollution level due to our assumption that $R_{tp} < 0$. Formally,

[11] The effect via changes in the own country tax rate vanishes due to the envelope theorem.

Proposition 1 *When the two countries do not respond to a terms-of-trade shock by adjusting their Nash emission tax rates, then an improvement in the terms of trade of a country reduces the aggregate level of pollution, and increases its welfare, if it imports the polluting good.*

We now consider the case where the two countries responds to a terms-of-trade shock by reoptimizing and thus adjusting the Nash equilibrium emission tax rates. Recall that $A_{t^*} > 0$ and $R_{tt} > 0$, and thus the induced effects increases welfare and reduces pollution emission if the improvements in the terms-of-trade raise the Nash tax rates. Sufficient conditions for the latter result were developed earlier in this section.

In order to avoid complexities, like before, we now consider two special cases. First, we consider the case of one-way cross-border pollution, $i.e.$, $\theta^* > 0$ and $\theta = 0$. In this case the effect of an improvement in the home country's terms of trade on its welfare is independent of adjustments in the foreign country's optimal emissions tax rate, since $A_{t^*} = 0$. Thus, the welfare effect of an exogenous terms of trade change is equivalent to that where there are no adjustments to the Nash equilibrium tax rate of the foreign country due to the exogenous terms of trade shocks. That is, trade liberalization improves welfare if the two countries import the polluting good. On the other hand, a terms-of-trade induced adjustment in the home country's Nash equilibrium tax rate does affect its aggregate level of pollution (equation (16)). If the country imports the polluting good, an improvement in the terms of trade reduces emission level if η_{zu} is sufficiently large (which is a sufficient condition for a terms-of-trade improvement to raise the Nash equilibrium emission tax, see equation (13)).

Second, turning to the case of symmetric countries, after suitable manipulations, equations (15) and (16) respectively become:

$$E_u \cdot \frac{du}{dp} = -M\left(1 - \frac{\theta\eta_{zu}}{\Delta z}E_z R_{tt}\right) - \theta\left(\frac{E_z}{\Delta}\right)(R_{tp} + R_{tt}E_{zp}), \tag{17}$$

$$\Delta \cdot \frac{de}{dp} = R_{tp} + R_{tt}\left(E_{zp} - \frac{M\eta_{zu}}{z}\right), \tag{18}$$

where $\Delta = (A_{tt} + A_{tt*})/R_{tt} < 0$.

First of all note that, in the absence of cross-border pollution, *i.e.*, $\theta = 0$, (17) reduces to $E_u du = -M dp$. This is the standard Copeland and Taylor (2003) result: an improvement in terms of trade always raises welfare. In the presence of cross-border pollution, however, sufficient conditions for this result to hold are that (i) the country imports the polluting good, and (ii) $E_{zp} \leq 0$. The latter condition requires that the polluting good and cleaner environment are weak-complements in consumption. Equation (18) also indicates that when the country (a) imports the polluting good and (b) $E_{zp} \leq 0$, then an improvement in the terms of trade reduces the level of aggregate pollution. If, however, $E_{zp} > 0$, then an improvement in its terms of trade reduces the level of aggregate pollution in the country if η_{zu} is sufficiently high. The above results are formally stated in the following proposition.

PROPOSITION **2** *Suppose the two countries are symmetric.*
1. An improvement in the terms of trade improves welfare if (i) the country is an importer of the polluting good, and (ii) the polluting good and the cleaner environment are weakly complements in consumption.
2. An improvement in the terms of trade reduces net emission if (i) the country is an importer of the polluting good, and (ii) the polluting good and the cleaner environment in consumption are either (a) weak-complements, or (b) substitutes and η_{zu} *is sufficiently high*

As compared to Copeland and Taylor (2003) where an improvement of terms of trade unambiguously increases welfare, here, in the presence of cross border pollution, we need additional conditions for an improvement in terms of trade to increase welfare, *viz.*, conditions (i) and (ii) in the above proposition. An improvement in the terms of trade can increase pollution in the foreign country (and thus increase cross-border pollution into the home country) if the exporting good is the polluting one ($R_{tp} > 0$) and if the polluting good and the cleaner environment are substitutes in consumption ($E_{pz} > 0$). In the latter case, i.e., when $E_{pz} > 0$, the foreign country reduces the optimal emission tax as a decrease in p

reduces the willingness to pay for cleaner environment there. In other words, when $R_{tp} > 0$ and $E_{pz} > 0$, an improvement in terms of trade can increase the level of cross border pollution and thus reduce welfare. This is the reason why we need conditions (i) and (ii) in proposition 2.

5 Perception of cross-border pollution and welfare

In this section we examine how changes in the perceptions of cross-border pollution, *i.e.*, changes in θ and θ^*, affect the Nash emission tax rates t^N and t^{*N}, and the levels of welfare in the two countries assuming that they adjust their Nash taxes in response to changes in θ and θ^*.

From equations (9) and (10) we obtain:

$$E_u E^*_{u^*} \Omega \cdot \frac{dt^N}{d\theta} = -B_{t^*t^*} A_{t\theta} = -e^* R_{tt} R^*_{t^*t^*} \left(\frac{E_z}{z}\right) (E^*_{z^*z^*} R^*_{t^*t^*} + 1)(-\varepsilon_{zz} + \eta_{zu}), \quad (19)$$

$$E_u E^*_{u^*} \Omega \cdot \frac{dt^N}{d\theta^*} = A_{tt^*} B_{t^*\theta^*} = -\theta e R_{tt} R^{*2}_{t^*t^*} \left(\frac{E_z E^*_{z^*}}{z z^*}\right) (-\varepsilon_{zz} + \eta_{zu})(-\varepsilon^*_{z^*z^*} + \eta^*_{z^*u^*}), \quad (20)$$

where $\Omega > 0$ is defined after equation (12).

Equation (19) indicates that a necessary and sufficient condition for an increase in the home country's spill-over parameter θ to increase the country's Nash equilibrium emission tax rate is that $\varepsilon_{zz} > \eta_{zu}$. That is, if the country's elasticity of marginal willingness to pay for pollution abatement with respect to pollution exceeds its elasticity of marginal utility of income with respect to pollution, then an increase in its spill-over parameter θ increases its Nash equilibrium emission tax rate.[12] On the other hand, equation (20) indicates that

[12] To illustrate better this point consider the following example. Suppose Scandinavian producers cause 100 units of pollution in Scandinavia, and residents of these countries originally think that another 80 units of pollution come from abroad, although the actual amount of cross-border pollution is 100 units. Now, suppose Scandinavian residents have an improved perception regarding cross-border pollution, where they think that 90 units of pollution come from abroad. Our result states that Scandinavian countries, under the conditions of the model, implement stricter controls on their own pollution. That is, their tolerance on their own pollution changes when the perception of total pollution changes. For example 100 units of local pollution may be more tolerable when total perceived pollution is 180 units, but less so when total perceived pollution is 190 units.

the impact of changes in the foreign country's rate of cross-border pollution θ^* on the home country's Nash tax rate t^N depends on the relationship between the two aforementioned elasticities in both countries. In particular, a necessary and sufficient condition for $dt^N/d\theta^*$ to be negative is that $(-\varepsilon_{zz}+\eta_{zu})$ and $(-\varepsilon^*_{z^*z^*}+\eta^*_{z^*u^*})$ are of the same sign. It is to be noted that if the utility functions are additively separable in the level of pollution (as is assumed in Copeland and Taylor (2003)), then it can be shown that $\varepsilon_{zz} > \eta_{zu}$ and $\varepsilon^*_{z^*z^*} > \eta^*_{z^*u^*}$, and thus $dt^N/d\theta > 0$ and $dt^N/d\theta^* < 0$. These results are stated formally in the following lemma.

Lemma 2 *An increase in the perception of cross-border pollution in a country increases the Nash emission tax in that country if and only if $\varepsilon_{zz} > \eta_{zu}$, and reduces the Nash emission tax in the other country if and only if $(-\varepsilon_{zz} + \eta_{zu})(-\varepsilon^*_{z^*z^*} + \eta^*_{z^*u^*}) > 0$.*

The above result can be explained as follows. An increase in θ to start with, reduces welfare in the home country. This reduction in utility reduces people's willingness to pay for reduced pollution and thus the government reduces the tax rate. The magnitude of this reduction depends on that of η_{zu}. An increase in z induced by an increase in θ on the other hand increases people's willingness to pay for pollution reduction, and the government increases the optimal tax rate. The magnitude of this increase depends on the size of ε_{zz}. The net effect on the Nash tax is then positive if and only if $\varepsilon_{zz} > \eta_{zu}$. An increase in θ^* similarly increases the Nash emission tax in the foreign country if and only if $\varepsilon^*_{z^*z^*} > \eta^*_{z^*u^*}$. An increase in the foreign country's Nash emission tax reduces the level of cross-border pollution into the home country, and this reduction in cross-border pollution increases the Nash emission tax in the home country, for reasons mentioned above, if and only if $\varepsilon_{zz} < \eta_{zu}$. Taking the two effects into account, an increase in θ^* increases the Nash emission tax in the home country if and only if $(\varepsilon^*_{z^*z^*} - \eta^*_{z^*u^*})(\varepsilon_{zz} - \eta_{zu}) < 0$

Using equations (19) and (20) we next compute the effect of an increase in θ and θ^*

by an equal amount on the home country's Nash equilibrium tax rate t^N:

$$\begin{aligned} E_u E^*_{u^*}\Omega\left(\frac{dt^N}{d\theta}+\frac{dt^N}{d\theta^*}\right) &= -R_{tt}R^*_{t^*t^*}\left(\frac{E_z}{z}\right)(-\varepsilon_{zz}+\eta_{zu}) \\ &\cdot \left[e^*(E^*_{z^*z^*}R^*_{t^*t^*}+1)+\theta e R^*_{t^*t^*}\left(\frac{E^*_{z^*}}{z^*}\right)(-\varepsilon^*_{z^*z^*}+\eta^*_{z^*u^*})\right]. \end{aligned} \tag{21}$$

Equation (21) indicates that an equal increase in both θ and θ^* has an ambiguous effect on the home country's Nash equilibrium tax rate. This is because, as shown above, an increase in θ may have the opposite effect on the optimal tax rate than an increase in θ^*. However, a sufficient condition for such an increase to reduce t^N is that $\eta_{zu} > \varepsilon_{zz}$ and $\eta^*_{z^*u^*} > \varepsilon^*_{z^*z^*}$, and a sufficient condition for t^N to increase is that $\eta_{zu} < \varepsilon_{zz}$ and $\eta^*_{z^*u^*} > \varepsilon^*_{z^*z^*}$.

Turning to the welfare effects of changes in the perceived spill-over parameters θ and θ^*, we use equation (5) and the expression for $dt^{*N}/d\theta$ from the counterpart of equation (20) to obtain:

$$\begin{aligned} E_u\,\frac{du}{d\theta} &= A_\theta + A_{t^*}\cdot\frac{d{t^*}^N}{d\theta} \\ &= -\frac{E_z e^* R_{tt}R^*_{t^*t^*}(E_{zz}R_{tt}+1)(E^*_{z^*z^*}R^*_{t^*t^*}+1)}{E_u E^*_{u^*}\Omega} < 0. \end{aligned} \tag{22}$$

An increase in θ unambiguously reduces the country's welfare. A direct effect given by A_θ and an indirect effect via an induced change in the foreign country's Nash emission tax rate. The effect via a change in the home country's tax rate disappears because its initial value is optimally set (the envelope property). The direct effect is unambiguously negative and the indirect effect can be either positive or negative. However, the direct effect dominates, leading to a reduction in the home country's welfare.

A change in θ^* does not have a direct effect, but only an indirect effect via a change in t^{*N}. An increase in θ^* would increase the welfare in the home country if and only if $dt^{*N}/d\theta^* > 0$, and we know from the analysis above that $dt^{*N}/d\theta^* > 0$ if and only if

$\varepsilon^*_{z^*z^*} > \eta^*_{z^*u^*}$. Formally,

$$E_u \cdot \frac{du}{d\theta^*} = A_{t^*} \cdot \frac{dt^{*N}}{d\theta^*} \tag{23}$$
$$= -\frac{\theta e E_z R_{tt} R^{*2}_{t^*t^*} \left(\frac{E^*_{z^*}}{z^*}\right) (E_{zz}R_{tt} + 1)(-\varepsilon^*_{z^*z^*} + \eta^*_{z^*u^*})}{E_u E^*_{u^*} \Omega}.$$

Finally, from the above two equations and assuming that the spill-over parameters θ and θ^* change by the same amount, the resulting change in the home country's welfare is given as follows:

$$E_u^2 E^*_{u^*} \Omega \left(\frac{du}{d\theta} + \frac{du}{d\theta^*}\right) = -E_z R_{tt} R^*_{t^*t^*} (E_{zz}R_{tt} + 1) \tag{24}$$
$$\cdot \left[e^* + \eta^*_{z^*u^*} \theta e R^*_{t^*t^*} \left(\frac{E^*_{z^*}}{z^*}\right) - \left(\frac{E^*_{z^*}}{z^*}\right) \varepsilon^*_{z^*z^*} R^*_{t^*t^*} (\theta e - e^*)\right].$$

We know that an increase in θ reduces home welfare, and that an increase in θ^* reduces home welfare if and only if $\eta^*_{z^*u^*} > \varepsilon^*_{z^*z^*}$. Thus, $\eta^*_{z^*u^*} > \varepsilon^*_{z^*z^*}$ is a sufficient condition for an equal increase in θ and θ^* to reduce home welfare. However, if $\eta^*_{z^*u^*} < \varepsilon^*_{z^*z^*}$ it is possible that an equal increase in θ and θ^* increases home welfare. From the above equation, it follows that if $\theta > (e^*/e)$ and $\varepsilon^*_{z^*z^*}$ is sufficiently large then this will be the case. For example, this will be the case if foreign pollution is small relative to home pollution, the initial perception about cross-border pollution is high and the propensity parameter is small. These results are summarized in the following proposition.

Proposition **3** *(i) An increase in the perception of cross-border pollution in the home country (a) unambiguously reduces its welfare and (b) increases the welfare in the other country if and only if $\varepsilon_{zz} > \eta_{zu}$. (ii) An equal increase in the perception of cross-border pollution in the two countries will reduce welfare in the home (foreign) country if $\eta^*_{z^*u^*} > \varepsilon^*_{z^*z^*}$ ($\eta_{zu} > \varepsilon_{zz}$). (iii) An equal increase in the perception of cross-border pollution in the two countries will increase welfare in the home (foreign) country if (a) $\theta > (e^*/e)$ ($\theta^* > e/e^*$) and $\varepsilon^*_{z^*z^*}$ (ε_{zz}) is sufficiently large.*

6 Concluding Remarks

In the absence of pollution, changes in world prices of traded goods affects welfare by changing the value of trade. This is the well-known terms-of trade effect. For example, a decrease in the relative price of the imported good increases welfare by decreasing the value of imports. In the presence of cross-border pollution, changes in world prices of goods has an additional effect on welfare, on top of the term-of-trade effect, by changing government behavior insofar as the choice of optimal emission taxes are concerned. In order to analyze this additional effect, we build a two-country, two-good, general equilibrium trade model. The production of one of the goods in each country generates pollution which is also transmitted to the other country. In response to pollution each country imposes an emission tax in a non-cooperative fashion.

The reduction in the world price of the polluting good which is imported by the home country — which can be a result of a decrease in trade costs — improves its welfare by decreasing the cost of imports, but it can also have an additional welfare-increasing effect by decreasing pollution transmitted from the foreign country. For example, if this decrease in the price of the polluting good causes the foreign country's Nash equilibrium emission rate to increase, then this indirect effect will strengthen the beneficial effect of a terms-of-trade improvement. The decrease in the price of the polluting good in fact causes the foreign country's Nash equilibrium emission rate to increase if, *inter alia*, the polluting good and clean environment are complements or independent in consumption and the two countries are importers of the polluting good. If, however, the country exports the polluting good, an improvement in its terms of trade may decrease its welfare.

We also examine effect of a change in the perception about the extent of cross-border pollution on welfare levels in the two countries. We find that an increase in such a perception in a country unambiguously decreases welfare in that country, but may increase welfare in the other country. Thus, an increase in the perception in both countries can in principle increase welfare in the two countries.

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