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WELFARE RANKING OF ENVIRONMENTAL POLICIES IN THE PRESENCE OF CAPITAL MOBILITY AND CROSS-BORDER POLLUTION

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Abstract

We construct a general equilibrium model of two regions with cross-border pollution, and with inter-regional (RCM) or international (ICM) capital mobility. Each region uses emission taxes, or intra- regionally, or inter-regionally tradable emission permits to reduce pollution. We show that the non-cooperative settings of all three instruments are always inefficient relative to their cooperative settings. When regions are symmetric, then (i) with RCM the non-cooperative setting of intra-regionally tradable emissions permits is welfare superior to that of the other two instruments, and (ii) with ICM the non-cooperative settings of intra-regionally tradable emission permits and of emission taxes are equivalent and superior to that of inter-regionally tradable emission permits.

Keywords: Cross-border pollution, Tradable emission permits, Capital mobility, Welfare ranking

J.E.L Classification: F18, F21, H21

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Welfare Ranking of Environmental Policies in the Presence of Capital Mobility and Cross-border Pollution

1. Introduction

With the signing of the Kyoto protocol in 1997, tradable emission permits were advocated as a viable instrument in controlling international pollution externalities, e.g., greenhouse gases. The introduction and implementation of tradable emission permits have given rise to a wide range of theoretical and policy related issues which have lead to an extensive economics literature on this subject.[1] Tradable emission permits have been advocated as a more "equitable" cost-effective environmental policy instrument relative to other command-and-control environmental measures, e.g., different emissions standards at every different source of pollution, e.g., Ellerman *et al.* (2003). It is argued, however, that a tradable permits system entails a trade-off between greater efficiency due to expansion of national or international permits markets and the risk of creating "hot spots", i.e., location enclaves where the increased trading of permits may exacerbate the creation of cross-border pollution emissions. Nowadays, the two leading users of tradable emission permits schemes are the EU with the Emissions Trading Scheme (EU-ETS), for controlling transnational CO_2 emissions by large industrial sources, and the US with the Sulfur Allowance Trading Scheme (US-SATS) to control inter-States emissions of Sulfur Dioxide (SO_2).[2]

The present paper contributes to the literature on tradable emission permits in two ways. In a framework with capital mobility and cross-border pollution, we examine, first, whether and under what conditions, the non-cooperative and cooperative equilibrium level of intra or inter-regionally tradable emission permits are equally welfare efficient. Second, at Nash equilibrium, which permits regime, and under what conditions, welfare dominates the other. To provide a

[1] Such issues are: (i) whether a decentralized permits system provides better abatement cost efficiency, i.e., Malueg and Yates (2009), and Dijkstra et al. (2011), (ii) whether tradable emission permits should be auctioned or distributed freely to polluting firms, e.g., sees Mæstad (2007), (iii) whether the so-called *cap-and-trade* permits programs are more effective relative to the so-called *credit-based* permits programs, e.g., see Norrengraad and Reppelin-Hill (2000).

[2] The EU-ETS is a decentralized regulatory system in which each Member Sate unilaterally allocates an endowment of emission permits to the permits market, e.g., Ellerman and Joskow (2008). The sum of these permits constitutes the supply of CO_2 permits. By the US-SATS system the supply of emission permits is determined by a single regulatory authority.

comprehensive examination of these issues, the analysis also presents the results of the case where emission taxes are the policy instrument.[3]

The issue of efficiency of the non-cooperative vs. the cooperative equilibrium of environmental policy is the subject of a small and recently expanding literature. It begins with the seminal contribution by Oates and Schwab (1988). In a model of many small jurisdictions with capital mobility and local pollution, they show that the non-cooperative (Nash) and cooperative setting of environmental standards are equally efficient, when the regions set optimally, i.e., equal to zero, capital taxes. Ogawa and Wildasin (2009) demonstrate the welfare efficiency of decentralized policymaking in a framework similar to that of Oates and Schwab (1988) where pollution, related to the use of capital, is transboundary and capital taxes are the sole instrument of controlling pollution. Petchey (2014) extends the Oates and Schwab result by considering large open-economy jurisdictions, where the return to capital is endogenous.[4] Tsakiris *et al.* (2015) in a model with international capital mobility and public pollution abatement, show, among other things, that when cross-border pollution is perfect, the decentralized setting of inter-regionally tradable emission permits is always efficient, while the decentralized setting of intra-regionally tradable emission permits is inefficient.

The aforementioned literature with capital mobility and pollution has by and large considered capital taxes alone or capital taxes and pollution standards as the relevant environmental policy instruments. In regards to this, two considerations are raised. First, capital taxes may not be the most appropriate instrument of environmental policy. Second, nowadays, locally or internationally tradable emission permits constitute an important instrument for combating environmental degradation. Combining capital mobility, cross-border pollution, and the use of tradable emission permits, remains a rather thin part of the literature on environmental

[3] An important strand of the literature, of interest to our analysis, examines whether nationally tradable emission permits welfare dominate internationally tradable emission permits. In the absence of international capital mobility and with cross-border pollution Copeland and Taylor (1995, 2005), Helm (2003), and more recently Lapan and Sikdar (2011) and Antoniou *et al.* (2014) consider, within various analytical contexts, whether the issuance of internationally versus nationally traded emission permits can lead to superior outcomes when countries act non-cooperatively. Chen and Woodland (2013), Neary (2006), Copeland and Taylor (2004) provide extensive overviews of broad environmental-international trade related issues.

[4] Eichner and Runkel (2012), Fell and Kaffine (2014) are recent, but not directly relevant to our analysis, extensions of the Ogawa and Wildasin (2009) contribution.

policy.[5] The present paper encompasses these features in a general equilibrium model of two regions.

We highlight the following results. In the presence of cross-border pollution, the non-cooperative settings of all three instruments are always inefficient relative to their cooperative settings, regardless of the regime of capital mobility. When regions are symmetric, then (i) with inter-regional capital mobility the non-cooperative setting of intra-regionally tradable emissions permits is welfare superior to that of the other two instruments, and (ii) with international capital mobility the non-cooperative settings of intra-regionally tradable emission permits and of emission taxes are equivalent and are superior to that of inter-regionally tradable emission permits. With perfect cross-border pollution, the non-cooperative settings of the three policy instruments are equivalent under international capital mobility. With inter-regional capital mobility the non-cooperative settings of the two types of tradable emission permits are equivalent and are welfare superior to that of emission taxes.

2. The Model

We consider a general equilibrium model of two regions, Home and Foreign. Both regions produce, consume and trade freely many goods. In each region prices of goods are assumed fixed.[6] In both regions, production of good 1 generates pollution while production and consumption of all other goods are non-polluting. Production generated pollution is transmitted across regions, affecting negatively the utility of residents in both regions.[7] In controlling pollution, the regions resort to one of two alternative ways of emission controls. Emission permits which are traded either within a region in a local permits market by local producers, or across regions in an inter-regional permits market by producers from both. There is a fixed capital endowment in each region and $\bar{K}\left(\bar{K}^{*}\right)$ denotes Home's (Foreign's) capital endowment.[8] Hereon, an asterisk denotes Foreign's variables. We consider two regimes of capital mobility.

[5] This literature includes works by Mæstad (2006, 2007), and Jouvet and Rotillon (2012), but on completely different issues to the ones addressed here.

[6] Oates and Schwab (1988), Mæstad (2006, 2007), Ogawa and Wildasin (2009) all employ this assumption to rule out leakage (terms of trade) effects through product markets.

[7] Kotsogiannis and Woodland (2013) examine the case where production pollution affects national production by impacting upon effective factor endowments.

[8] This assumption is in line with the relevant literature where all studies, whether consider a two-region framework, e.g., Mæstad (2006, 2007), or a multi-region (jurisdictions) framework, e.g., Oates and Schwab (1988), Ogawa and Wildasin (2009), treat the total stock of, nationally and internationally mobile, capital as fixed.

One, which we call *inter-regional capital mobility* (RCM), whereby capital is freely mobile only between the two regions, and its rate of return is endogenously determined and is equalized across them. The other, which we call *international capital mobility* (ICM), whereby capital is freely mobile between the two regions and between each region and the rest of the world. In this case, the rate of return to capital in each region is fixed and equal to its world rate of return. All other factors of production are inter-regionally immobile and inelastically supplied. Factor markets in both regions are perfectly competitive.

Production generated pollution in Home and Foreign are denoted respectively by z and z^*. Let $0 \le \theta \le 1$ and $0 \le \theta^* \le 1$ be the rates of pollution transmitted from Foreign to Home and vice-versa.[9] The aggregate levels of pollution in Home (r) and Foreign (r^*) are:

$$r = z + \theta z^* \quad \text{and} \quad r^* = z^* + \theta^* z . \tag{1}$$

We denote by s_i, where $i = n, t$ the price of emission permits. When permits are intra-regionally tradable, their price s_n is determined locally in the region's permits market; when permits are inter-regionally tradable, their price s_t is determined in the inter-regional permits market. The production side of Home is represented by the revenue function which, since prices of goods are fixed, is written as $R(s_i, K)$. The level of pollution z is given by $z(= \partial R / \partial s_i) = -R_{s_i}(s_i, K)$. $R_K (= \partial R / \partial K)$ denotes the marginal revenue product of capital. We assume that the $R(s_i, K)$ function is strictly concave in K, i.e., $R_{KK} < 0$, and strictly convex in s_i, i.e., $R_{s_i s_i} > 0$. The latter assumption implies that lower number of permits raises the price of emission permits and lowers the level of pollution. It is assumed that an inflow of capital raises the production of the polluting good, thus leading to higher levels of pollution, i.e., $dz / dK > 0$. That is, $R_{s_i K}$ is assumed negative. Similarly, Foreign's revenue function is $R^*(s_i^*, K^*)$, where $K^* \le \bar{K}^* - k$ is the amount of capital operating in Foreign. Foreign's level of production generated pollution is $z^* = -R_{s_i^*}(s_i^*, K^*)$. It is also assumed that $R^*_{s_i^* K^*} < 0$.

Each region comprises identical individuals whose utility is adversely affected by pollution. The demand side is represented by the minimum expenditure function $E(r, u)$, capturing a representative individual's minimum expenditure on goods required to attain a given

[9] For example, $\theta = 0$ denotes purely local pollution, $\theta = 1$ denotes perfectly cross-border pollution.

level of utility (u), at given consumer prices and overall pollution in the region. Consumer prices are omitted from the expenditure function since they are constant. The partial derivative $E_r (= \partial E / \partial r)$ denotes the household's *marginal willingness to pay* for reduction in pollution or the *marginal environmental damage*, and is positive since pollution is a public bad, e.g., Copeland and Taylor (2004). The partial derivative $E_u (= \partial E / \partial u)$ gives the reciprocal of the marginal utility of income. Similarly, Foreign's minimum expenditure function is given by $E^*(r^*, u^*)$.

In what follows, we examine the regions' Nash and cooperative equilibrium environmental policies, with intra-regionally and inter-regionally tradable emission permits, in the presence of cross-border pollution and either (RCM) or (ICM).

3. RCM, Emission Control Policies and Welfare

With RCM, equilibrium in the inter-regional capital market requires that the marginal revenue product of capital is equated across the two regions.[10]

$$R_K(s_i, K) = R^*_{K^*}(s^*_i, K^*), \tag{2}$$

Each region's income-expenditure identity requires that spending on goods equals income from production plus rents accruing from sales of emission permits, plus net payments to their capital located abroad. Without loss of generality Home (Foreign) is designated as the capital importing (exporting) region.

$$E(r,u) = R(K, s_i) + s_i Z_i - kR_K(s_i, K), \tag{3}$$

$$E^*(r^*, u^*) = R^*(K^*, s^*_i) + s^*_i Z^*_i + kR_K(s_i, K) \ , \tag{4}$$

where, $k > 0$ is the amount of Foreign's capital operating in Home.

3.1 Intra-regionally Tradable Permits

Emission permits issued by a regional government are traded locally, i.e., intra-regionally tradable, among producers in the region. Let Z_n and Z^*_n denote the levels of emission permits

[10] Equilibrium condition (2) is equivalent with capital markets equilibrium conditions set by, e.g., Oates and Schwab (1988), Ogawa and Wildasin (2009), whereby the net rate of return to capital is set so that total demand for capital by all jurisdictions equals the fixed aggregate capital supply.

issued by each region. We assume that one permit corresponds to a unit of pollution emissions. Assuming that these levels are binding, i.e., $z = Z_n$ and $z^* = Z_n^*$, the equilibrium prices of these permits, s_n in Home and s_n^* in Foreign, are determined in each region's permits market. Rents accruing from the auction of these permits are lump-sum distributed to the regions' households. The equilibrium for the two-region model is given by equations (2)-(4), where $i = n$, and the following permits markets equilibrium conditions:

$$-R_{s_n}(s_n, K) = Z_n, \tag{5}$$

$$-R^*_{s_n^*}(s_n^*, K^*) = Z_n^*. \tag{6}$$

Furthermore, in equations (3) and (4), $r = Z_n + \theta Z_n^*$ and $r^* = Z_n^* + \theta^* Z_n$.

Differentiating equations (2)-(6) gives the welfare effects of changes in the volume of intra-regionally tradable permits as

$$E_u \left(\frac{du}{dZ_n} \right) = s_n - E_r \frac{dr}{dZ_n} - k \left(R_{Ks_n} \frac{ds_n}{dZ_n} + R_{KK} \frac{dK}{dZ_n} \right) = A_{Z_n} = -(E_r - s_n) + \Delta_n^{-1} k R_{Ks_n} R^*_{K^*K^*} \tilde{R}^*_{s_n^* s_n^*}, \tag{7}$$

$$E^*_{u^*} \left(\frac{du^*}{dZ_n^*} \right) = s_n^* - E^*_{r^*} \frac{dr^*}{dZ_n^*} + k \left(R_{Ks_n} \frac{ds_n}{dZ_n^*} + R_{KK} \frac{dK}{dZ_n^*} \right) = A^*_{Z_n^*} = -(E^*_{r^*} - s_n^*) - \Delta_n^{-1} k R^*_{K^* s_n^*} R_{KK} \tilde{R}_{s_n s_n}, \tag{8}$$

where $\Delta_n = R_{KK} R^*_{s_n^* s_n^*} \tilde{R}_{s_n s_n} + R^*_{K^*K^*} R_{s_n s_n} \tilde{R}^*_{s_n^* s_n^*} < 0$, $\tilde{R}_{s_n s_n} = R_{s_n s_n} - R_{s_n K} R_{KK}^{-1} R_{Ks_n} > 0$ and $\tilde{R}^*_{s_n^* s_n^*} = R^*_{s_n^* s_n^*} - R^*_{s_n^* K^*} R^{*-1}_{K^*K^*} R^*_{K^* s_n^*} > 0$. See equations (A.2) in the Appendix for details. In equations (7)-(8) if $(E_r - s_n) > 0$ and $(E^*_{r^*} - s_n^*) > 0$, i.e., in each region the marginal environmental damage is higher than the price of emission permits, then a lower level of emission permits by either region increases its welfare through this term. Also, a lower level of emission permits affects a region's welfare through changes in payments to mobile capital. For example, for Home, the capital importing region, the effect of lower Z_n through payments to Foreign's capital operating locally is due to the induced permits price effect, i.e., $-kR_{Ks_n} \frac{ds_n}{dZ_n}$ and capital flow effect, i.e., $-kR_{KK} \frac{dK}{dZ_n}$, on Home's marginal revenue product of capital. The former effect reduces Home's marginal product of capital since $\frac{ds_n}{dZ_n} < 0$, while the latter effect increases it since $\frac{dK}{dZ_n} > 0$ (see equations A.2). Simple algebra shows that the price effect outweighs the capital flow effect and thus Home's welfare increases through the decrease in the payment of foreign capital when the number of emission permits decrease (i.e., $\Delta_n^{-1} k R_{Ks_n} R^*_{K^*K^*} \tilde{R}^*_{s_n^* s_n^*} < 0$). For Foreign, a decrease in Z_n^*, in addition to the standard $(E^*_{r^*} - s_n^*)$ effect, it also entails a negative effect on its welfare by decreasing the payments to its capital located in Home.

3.1.1 Nash vs. Cooperative equilibrium

Setting $A_{Z_n} = 0$ and $A^*_{Z_n^*} = 0$ in equations (7)-(8), we obtain each region's best-response function. Solving them gives the Nash equilibrium levels of intra-regionally tradable emission permits Z_n^N and Z_n^{*N} with capital mobility and cross-border pollution. The superscript (N) denotes the Nash equilibrium levels of tradable permits. When regions issue intra-regionally tradable emission permits in order to maximize their joint welfare, the levels of Z_n^C and Z_n^{*C}, respectively, are determined by setting $E_u(du/dZ_n) + E^*_{u^*}(du^*/dZ_n) = 0$ for Home and $E_u(du/dZ_n^*) + E^*_{u^*}(du^*/dZ_n^*) = 0$ for Foreign, where the superscript "C" denotes the cooperative equilibrium levels of tradable permits.

To examine whether or not the Nash equilibrium levels of intra-regionally permits are higher or lower relative to the cooperative ones, we evaluate the regions joint welfare at Nash equilibrium. Consider the choices Z_n^N and Z_n^C by Home. Since at Nash $E_u\left(du/dZ_n\right) = 0$, then the slope of the joint welfare function evaluated at the Nash equilibrium is given by $E^*_{u^*}\left(du^*/dZ_n\right)$. From the differentiation of equations (2) to (6) we also obtain:

$$E^*_{u^*}\left(\frac{du^*}{dZ_n}\right) = -\theta^* E^*_{r^*} - \Delta_n^{-1} k R^*_{K^* s_n^*} R_{KK} \tilde{R}_{s_n s_n} . \tag{9}$$

Equation (9) indicates that at Nash equilibrium, when $\theta^* \neq 0$, then $E^*_{u^*}\left(du^*/dZ_n\right) > (<) 0$, implying that Z_n^N can be higher or lower than Z_n^C. Put it differently, with cross-border pollution, the capital importing region follows either stricter or laxer environmental policy in the non-cooperative equilibrium vis-à-vis the cooperative equilibrium. When $\theta^* = 0$, then $E^*_{u^*}\left(du^* / dZ_n\right) > 0$, implying that $Z_n^N < Z_n^C$. That is, when the capital importing region acts non-cooperatively, relative to the cooperative equilibrium, it issues fewer permits which results to lower payments to Foreign's capital employed locally, thus positively affecting its own welfare and negatively Foreign's welfare.

Following a similar approach, Foreign sets $E_u(du / dZ_n^*) + E^*_{u^*}(du^* / dZ_n^*) = 0$ in order to choose Z_n^{*C} which maximizes the regions joint welfare. The slope of the joint welfare function evaluated at the Nash equilibrium is given by

$$E_u\left(\frac{du}{dZ_n^*}\right) = -\theta E_r + \Delta_n^{-1} k R_{Ks_n} R^*_{K^*K^*} \tilde{R}^*_{s_n^* s_n^*}. \tag{10}$$

The right-hand-side of equation (10) is unambiguously negative, indicating that the slope of the joint welfare function, when evaluated at Nash equilibrium, is negative. Thus, the capital exporting region's volume of emission permits under the non-cooperative equilibrium is always bigger than under the cooperative equilibrium, i.e., $Z_n^{*N} > Z_n^{*C}$. The following Proposition summarizes the results of this section.

Proposition 1: *Consider two regions with inter-regional capital mobility, cross-border pollution and where each region issues intra-regionally tradable emission permits to control pollution. The Nash equilibrium level of the intra-regionally tradable emission permits for the capital-exporting region is higher than the cooperative level, while for the capital-importing region it may be lower.*

3.2 Inter-regionally Tradable Emission Permits

Now each region issues emission permits which are tradable across them. Producers can raise production emissions above the level Z_t or Z_t^* set by their own region, by buying permits from the other region. The equilibrium condition for the inter-regional permits market, which determines their price s_t, is given by

$$z + z^* = -R_{s_t}(s_t, K) - R^*_{s_t}(s_t, K^*) = Z_t + Z_t^*. \tag{11}$$

The equilibrium conditions for the two regions are given by equations (2)-(4) and (11), where $i = t$, $r = z + \theta z^*$ and $r^* = z^* + \theta^* z$. Differentiating these equations gives the impact of changes in Z_t on Home's welfare as follows (see equations (A.3)-(A.5) in the Appendix for details):

$$\frac{du}{dZ_t} = s_t + (Z_t - z)\frac{ds_t}{dZ_t} + E_r\left[\left(R_{s_t s_t} + \theta R^*_{s_t s_t}\right)\frac{ds_t}{dZ_t} + \left(R_{s_t K} - \theta R^*_{s_t K^*}\right)\frac{dK}{dZ_t}\right] - k\left(R_{Ks_t}\frac{ds_t}{dZ_t} + R_{KK}\frac{dK}{dZ_t}\right). \quad (12)$$

The first RHS term in equation (12) is a direct revenue effect, indicating a negative impact on Home's welfare when at the given price s_t, the region issues fewer permits. $(Z_t - z)$ is positive (negative) if Home is a permits exporter (importer). Since $ds_t / dZ_t < 0$ (see equations A.4), the second RHS term entails a positive (negative) impact on Home's welfare if it is a permits exporter (importer). The third term is the impact of a lower Z_t on welfare through changes in the level of aggregate pollution. Given E_r, this effect unveils through changes in the price of inter-regionally tradable permits and Home's supply of capital. The last RHS term of equation (12) is the impact of a lower Z_t on Home's welfare through the change in payments to Foreign's capital operating in Home. This change in capital payments due to a lower Z_t is again due to the permits price effect, i.e., $-kR_{Ks_t}\frac{ds_t}{dZ_t}$, and the capital outflow effect, i.e., $-kR_{KK}\frac{dK}{dZ_t}$, on Home's marginal revenue product of capital.[11] Some manipulations in equation (12) result in:

$$E_u\left(\frac{du}{dZ_t}\right) = B_{Z_t} = \left\{\begin{array}{l} s_t\Delta_t + (Z_t - z)H_{KK} + E_r\left[\left(R_{s_t s_t} + \theta R^*_{s_t s_t}\right)H_{KK} - \left(R^*_{s_t K^*} - R_{s_t K}\right)\left(R_{s_t K} - \theta R^*_{s_t K^*}\right)\right] \\ -k\left(R_{KK}R^*_{s_t K^*} + R^*_{K^*K^*}R_{Ks_t}\right) \end{array}\right\}\Delta_t^{-1}, \quad (13)$$

where $\Delta_t = -H_{KK}H_{s_t s_t} + (R_{Ks_t} - R^*_{K^* s_t})^2 > 0$, and $H_{s_t s_t} = R_{s_t s_t} + R^*_{s_t s_t} > 0$. Equation (13) shows that, overall, when Home issues fewer inter-regionally tradable emission permit, its payments to

[11] Contrary to the case of intra-regionally tradable permits (see equations A.2), where $\frac{dK}{dZ_n} = R_{Ks_n}R^*_{s^*_n s_n}\Delta_n^{-1} > 0$, with inter-regionally tradable permits we have $\frac{dK}{dZ_t} = -\Delta_t^{-1}\left(R_{Ks_t} - R^*_{K^* s_t}\right) > (<) 0$. If $\left(R_{Ks_t} - R^*_{K^* s_t}\right)$ is positive, then a lower Z_t by Home has a positive welfare impact through the capital flow effect in addition to the positive price effect on the region's marginal revenue product of capital.

foreign capital are reduced which exerts a positive impact on its welfare i.e., $-k\left(R_{KK}R^{*}_{s_tK^{*}}+R^{*}_{K^{*}K^{*}}R_{Ks_t}\right)\Delta_t^{-1}<0$. Equivalently we can derive:

$$E^{*}_{u^{*}}\left(\frac{du^{*}}{dZ^{*}_t}\right)=B^{*}_{Z^{*}_t}=\left\{\begin{matrix} s_t\Delta_t+E^{*}_{r^{*}}\left[\left(R^{*}_{s_ts_t}+\theta^{*}R_{s_ts_t}\right)H_{KK}-\left(R^{*}_{s_tK^{*}}-\theta^{*}R_{s_tK}\right)\left(R_{s_tK}-R^{*}_{s_tK^{*}}\right)\right] \\ +(Z^{*}-z^{*})H_{KK}+k\left(R_{KK}R^{*}_{s_tK^{*}}+R^{*}_{K^{*}K^{*}}R_{Ks_t}\right) \end{matrix}\right\}\Delta_t^{-1} \tag{14}$$

$$E_u\left(\frac{du}{dZ^{*}_t}\right)=E_u\left(\frac{du}{dZ_t}\right)-s_t\,, \quad E^{*}_{u^{*}}\left(\frac{du^{*}}{dZ_t}\right)=E^{*}_{u^{*}}\left(\frac{du^{*}}{dZ^{*}_t}\right)-s_t\,. \tag{15}$$

3.2.1 Nash vs. Cooperative equilibrium

Setting $B_{Z_t}=0$ and $B^{*}_{Z^{*}_t}=0$ in equations (13) and (14) yields the regions' best-response functions which are solved for the Nash equilibrium levels of inter-regionally tradable emission permits Z_t^{N} and Z_t^{*N}. When Home chooses the levels of inter-regionally tradable emission permits cooperatively, i.e., so as to maximize their joint welfare, sets $E_u(du/dZ_t)+E^{*}_{u^{*}}(du^{*}/dZ_t)=0$ which yields the level Z_t^{C}. Similarly, Foreign sets $E_u(du/dZ^{*}_t)+E^{*}_{u^{*}}(du^{*}/dZ^{*}_t)=0$ to determine the level Z_t^{*C}. To compare the cooperative levels Z_t^{C} and Z_t^{*C} with the corresponding Nash levels Z_t^{N} and Z_t^{*N}, we evaluate the slope of the regions joint welfare function at Nash equilibrium. Recall that at Nash equilibrium $E_u(du/dZ_n)=0$ and $E^{*}_{u^{*}}(du^{*}/dZ^{*}_t)=0$. Then, using equations (15), the slope of the joint welfare function in each case is given by:

$$E_u\left(\frac{du}{dZ^{*}_t}\right)=E^{*}_{u^{*}}\left(\frac{du^{*}}{dZ_t}\right)=-s_t\,. \tag{16}$$

Equation (16) reveals that the slope of the joint social welfare function at Nash equilibrium is negative, implying that $Z_t^{N}>Z_t^{C}$ and $Z_t^{*N}>Z_t^{*C}$. Thus, with inter-regionally tradable emission permits, both the capital importing and exporting regions pursue a laxer environmental policy when they act non-cooperatively compared to when they act cooperatively.

Proposition 2: *Consider two regions with inter-regional capital mobility, cross-border pollution and where each region issues inter-regionally tradable emission permits to control pollution.*

The Nash equilibrium level of the inter-regionally tradable emission permits for each region is higher than the cooperative level.

3.3 Emission Taxes

For completeness of our analysis and policy ranking, we now briefly present the case where pollution is controlled via emission taxes. Since the relevant literature offers ample discussion of related results, e.g., Copeland and Taylor (2004), Hadjiyiannis *et al.* (2009), we defer to the Appendix, i.e., equations (A.6)-(A.12), details regarding the model structure of this case. From these equations we obtain:

$$E_u \frac{du}{d\tau} = D_\tau = (E_r - \tau)\tilde{R}_{\tau\tau} + \theta E_r H_{KK}^{-1} R_{K\tau} R^*_{\tau^* K^*} - kR^*_{K^* K^*} H_{KK}^{-1} R_{K\tau} \tag{17}$$

$$E^*_{u^*} \frac{du^*}{d\tau^*} = D^*_{\tau^*} = (E^*_{r^*} - \tau^*)\tilde{R}^*_{\tau^*\tau^*} + \theta^* E^*_{r^*} H_{KK}^{-1} R_{K\tau} R^*_{\tau^* K^*} + kR^*_{K^* K^*} H_{KK}^{-1} R_{K\tau}, \tag{18}$$

$$E_u \frac{du}{d\tau^*} = (E_r - \tau) R_{\tau K} H_{KK}^{-1} R^*_{K^*\tau^*} + \theta E_r \tilde{R}^*_{\tau^*\tau^*} - kR^*_{K^* K^*} H_{KK}^{-1} R_{K\tau}, \tag{19}$$

$$E^*_{u^*} \frac{du^*}{d\tau} = (E^*_{r^*} - \tau^*) R^*_{\tau^* K^*} H_{KK}^{-1} R_{K\tau} + E^*_{r^*} \theta^* \tilde{R}_{\tau\tau} + kR^*_{K^* K^*} H_{KK}^{-1} R_{K\tau}. \tag{20}$$

3.3.1 Nash vs. Cooperative equilibrium

Setting $D_\tau = 0$ and $D^*_{\tau^*} = 0$ in equations (17) and (18) gives the regions' best-response functions which can be solved for the Nash equilibrium emission taxes τ^N and τ^{*N}. When the two regions choose their emission taxes cooperatively so as to maximize their joint welfare, Home sets $E_u(du/d\tau) + E^*_{u^*}(du^*/d\tau) = 0$ which yields the rate τ^C and equivalently, Foreign sets $E_u(du/d\tau^*) + E^*_{u^*}(du^*/d\tau^*) = 0$ to determine the rate τ^{*C}.

We consider the case of Home, and we examine whether when the region acts non-cooperatively, its choice of emission tax τ^N is equally efficient to the emission tax τ^C when it acts cooperatively. Since at Nash equilibrium $E_u\left(du/d\tau\right) = E^*_{u^*}\left(du^*/d\tau^*\right) = 0$ the slope of the joint welfare function at Nash equilibrium is given by $E^*_{u^*}\left(du^*/d\tau\right)$. If $E^*_{u^*}\left(du^*/d\tau\right)$ is positive (negative) then the Nash equilibrium emission tax is lower (higher) than the cooperative equilibrium tax rate. A similar approach is followed for the capital exporting region. We state the following Proposition:

Proposition 3: *Consider two regions with inter-regional capital mobility, cross-border pollution and where emission taxes are used to control pollution. The capital importing region's Nash emission tax rate can be either higher or lower than its cooperative equilibrium emission tax rate. The capital exporting region's Nash equilibrium emission tax rate is always lower than its cooperative rate.*
Proof: see Appendix A.IV.

3.4 Welfare Ranking of Emission Control Policies under RCM

To provide the welfare ranking of the three emission control instruments when regions act non-cooperatively, we assume, along the lines of the relevant literature, that the regions are symmetric in the sense that they have identical preferences, factor endowments and production technologies. The latter assumption implies that $k=0$ and thus capital payments between the two regions cancel out. In this case, the welfare ranking of the three emission control policies depends solely on the overall level of pollution. Thus, the emission control policy regime which leads regions to choose a stricter environmental policy, i.e., either lower level of emission permits or higher emission tax, ensures lower pollution level and higher welfare. Under these considerations and in terms of our welfare analysis, using equations (7) or (8), (13) or (14), and (17) or (18), we obtain the following results:

Intra-regionally tradable emission permits: $s_n^N = E_r$, (21)

Inter-regionally tradable permits: $s_t^N = \dfrac{(1+\theta)}{2} E_r$,[12] (22)

Emission taxes: $\tau^N = E_r + \theta E_r \left(\tilde{R}_{\tau\tau} H_{KK}\right)^{-1} R_{K\tau} R^*_{\tau^* K^*}$. (23)

Equation (21) indicates that at Nash equilibrium, the regions' choice of intra-regionally tradable emission permits is such that their Nash equilibrium price is equal to the marginal environmental damage, i.e., $s_n^N = E_r$. Equations (22) and (23), respectively, give the Nash

[12] Because of the symmetry assumption, in equation (13) or (14), $E_r = E^*_{r^*}$, $R_{s_t K} = R^*_{s_t K^*}$, $k=0$, and $\Delta_t = -H_{KK} H_{s_t s_t}$. Making use of equation (11), we have, $Z_t = z$. Then, setting $du/dZ_t = 0$ we obtain equation (22).

equilibrium choice of inter-regionally tradable emission permits, and of emission taxes. Consider, for example the case of Home, and let $0 \le \theta < 1$. By equation (22), the coefficient of E_r is less than one, indicating that $s_t^N < E_r \left(= s_n^N\right)$. In this case, at Nash equilibrium, Home issues a larger number of inter-regionally tradable emission permits compared to the Nash equilibrium level of intra-regionally tradable permits. Thus, pollution is higher and welfare is lower in the former policy regime relatively to the latter. Using equation (23), when $\theta \neq 0$, we get a similar result for the Nash equilibrium emission tax τ^N, since $\tau^N < E_r \left(= s_n^N\right)$. When $\theta = 1$, equation (22) indicates that $s_t^N = E_r \left(= s_n^N\right)$, thus at Nash equilibrium, the region issues the same volume of intra or inter-regionally tradable emission permits, leading to the same level of pollution and welfare. From equation (23) we have that $\tau^N < E_r$, implying that the choice of the emission tax results to a higher level of pollution and lower welfare compared to the other two policy regimes. Finally, when $\theta = 0$, then $s_n^N = \tau^N = E_r > s_t^N$, implying that with local pollution, intra-regionally tradable emission permits and emission taxes lead to the same levels of pollution and welfare. Under inter-regionally tradable permits, however, pollution is higher and welfare is lower compared to the previous two policy regimes. The following proposition summarizes the welfare ranking of the three policy instruments.

Proposition 4: *Consider two symmetric regions with inter-regional capital mobility and cross border pollution. The ranking of the welfare levels* (u) *of the three emission control policies when are chosen non-cooperatively are:*

(i) If $0 < \theta < 1$, *then* $u_{Intra-regionally} > u_{Inter-regionally}$ and $u_{Intra-regionally} > u_{Emission\ tax}$,

(ii) If $\theta = 1$, *then* $u_{Intra-regionally} = u_{Inter-regionally} > u_{Emission\ tax}$,

(iii)If $\theta = 0$, then $u_{Intra-regionally} = u_{Emission\ tax} > u_{Inter-regionally}$.

4. ICM, Emission Control Policies and Welfare

We now consider the case where there is perfect international capital mobility between the two regions and between each region and the rest of the world. Each region is small in the world capital markets and thus the rate of return to capital is fixed. Equilibrium in each region's capital market requires that the rate of return to capital equals the world rate of return (ρ). That is:

$$R_K(s_i, K) = \rho \quad \text{and} \quad R^*_{K^*}(s^*_i, K^*) = \rho. \tag{24}$$

Each region's income-expenditure identity requires that spending on goods equals income from production plus rents accruing from sales of emission permits plus net payments to their capital located abroad.

$$E(r,u) = R(K, s_i) + s_i Z_i + \rho k, \tag{25}$$

$$E^*(r^*, u^*) = R^*(K^*, s^*_i) + s^*_i Z^*_i + \rho k^*. \tag{26}$$

In this case, $k > 0 (< 0)$ is the amount of Home's (Foreign and the rest of the world) capital operating in Foreign and in the rest of the world (Home). Similarly, $k^* > 0 (< 0)$ is Foreign's (Home and the rest of world) capital operating in Home and the rest of the world (Foreign).

4.1 Intra-regionally tradable emission permits

First we consider the case where the government of each region issues emission permits which are intra-regionally tradable. Using equations (5), (6) and (24)-(26) where $i = n$, we get the welfare effects of a change emission permits as follows:

$$E_u \frac{du}{dZ_n} = -E_r \frac{dr}{dZ_n} + s_n = -(E_r - s_n) \quad \text{and} \quad E^*_{u^*} \frac{du^*}{dZ^*_n} = -(E^*_{r^*} - s^*_n), \tag{27}$$

$$E_u \frac{du}{dZ^*_n} = -\theta E_r, \quad \text{and} \quad E^*_{u^*} \frac{du^*}{dZ_n} = -\theta^* E^*_{r^*}. \tag{28}$$

Setting $E_u \frac{du}{dZ_n} = 0$ and $E^*_{u^*} \frac{du^*}{dZ^*_n} = 0$ in equations (27), we obtain the Nash equilibrium levels of emission permits Z^N_n and Z^{*N}_n.

To compare the non-cooperative level Z^N_n with the level chosen in the cooperative equilibrium Z^C_n, we evaluate the joint welfare function at Nash equilibrium. Since at Nash equilibrium $E_u \frac{du}{dZ_n} = 0$, the slope of the joint welfare function is given by $E^*_{u^*} \left(du^* / dZ_n \right)$, which is negative (see equation 28). Similar analysis follows for Foreign. Therefore, when the regions are small in world capital markets and use intra-regionally tradable emission permits to control pollution, then the Nash equilibrium levels of permits are above the levels that maximize the joint welfare. Put it differently, in the non-cooperative equilibrium more pollution is generated relative to the cooperative equilibrium. When pollution is local i.e., $\theta = \theta^* = 0$, then the Nash equilibrium levels of permits for both regions coincide with the cooperative ones i.e., $Z_n^N = Z_n^C$ and $Z_n^{*N} = Z_n^{*C}$.

4.2 Inter-regionally tradable emission permits

The two regions issue inter-regionally tradable emission permits to control pollution. Differentiating equations (11) and (24)-(26) where $i = t$, we obtain the welfare effects of an increase in the intra-regionally tradable emission permits as follows:

$$\tilde{H}_{s_t s_t} E_u \frac{du}{dZ_t} = s_t \tilde{H}_{s_t s_t} - (Z_t - z) - E_r \left(\tilde{R}_{s_t s_t} + \theta \tilde{R}^*_{s_t s_t} \right), \tag{29}$$

$$\tilde{H}_{s_t s_t} E^*_{u^*} \frac{du^*}{dZ^*_t} = s_t \tilde{H}_{s_t s_t} - (Z^*_t - z^*) - E^*_{r^*} \left(\tilde{R}^*_{s_t s_t} + \theta^* \tilde{R}_{s_t s_t} \right), \tag{30}$$

$$E_u \frac{du}{dZ^*_t} = E_u \frac{du}{dZ_t} - s_t \quad \text{and} \quad E^*_{u^*} \frac{du^*}{dZ_t} = E^*_{u^*} \frac{du^*}{dZ^*_t} - s_t \,. \tag{31}$$

where $\tilde{H}_{s_t s_t} = \tilde{R}_{s_t s_t} + \tilde{R}^*_{s_t s_t} > 0$, $\tilde{R}_{s_t s_t} = R_{s_t s_t} - R_{s_t K} R^{-1}_{KK} R_{K s_t}$ and $\tilde{R}^*_{s_t s_t} = +R^*_{s_t s_t} - R^*_{s_t K^*} R^{*-1}_{K^* K^*} R^*_{K^* s_t}$. Setting $E_u \dfrac{du}{dZ_t} = 0$ and $E^*_{u^*} \dfrac{du^*}{dZ^*_t} = 0$, in equations (29) and (30) we obtain the Nash equilibrium levels of emission permits Z_t^N and Z_t^{*N}.

We proceed with the comparison of the non-cooperative equilibrium level of emission permits Z_t^N with the cooperative equilibrium level Z_t^C following similar steps as in previous sections. Evaluated at Nash equilibrium the slope of the joint welfare function is given by $E_u \left(du / dZ_t \right) + E^*_{u^*} \left(du^* / dZ_t \right) = E^*_{u^*} \left(du^* / dZ_t \right)$. From equations (31) we see that $E^*_{u^*} \left(du^* / dZ_t \right) = E^*_{u^*} \left(du^* / dZ^*_t \right) - s_t$ which is negative since at Nash equilibrium $E^*_{u^*} \left(du^* / dZ^*_t \right) = 0$. Therefore, when Home issues inter-regionally tradable emission permits to control pollution, then their Nash equilibrium level is inefficient and above the level that maximizes the joint welfare. The result holds independently of the rate of cross-border pollution.[13] A similar analysis holds for Foreign.

4.3 Emission taxes

The equilibrium conditions for two regions are given by the capital markets equilibrium conditions, equations (24), and the budget constraints, equations (25) and (26). Emission tax revenues denoted by τz for Home and $\tau^* z^*$ for Foreign are lump-sum distributed. It can be easily shown that the welfare effects of changes in emission taxes are given as follows:

$$E_u \frac{du}{d\tau} = -(E_r - \tau)\frac{dz}{d\tau} \quad \text{and} \quad E^*_{u^*} \frac{du^*}{d\tau^*} = -(E^*_{r^*} - \tau^*)\frac{dz^*}{d\tau^*}, \tag{32}$$

$$E_u \frac{du}{d\tau^*} = -\theta E_r \frac{dz^*}{d\tau^*} > 0 \quad \text{and} \quad E^*_{u^*} \frac{du^*}{d\tau} = -\theta^* E^*_{r^*} \frac{dz}{d\tau} > 0. \tag{33}$$

where $\frac{dz}{d\tau} = -\tilde{R}_{\tau\tau} = -(R_{\tau\tau} - R_{K\tau} R^{-1}_{KK} R_{\tau K}) < 0$. Setting $E_u \frac{du}{dZ_t} = 0$ and $E^*_{u^*} \frac{du^*}{dZ^*_t} = 0$ in equations (32) we obtain the Nash equilibrium emission taxes τ^N and τ^{*N}.

As in the previous cases, the slope of the joint welfare function at the Nash equilibrium for Home is given by $E_u\left(du/d\tau\right) + E^*_{u^*}\left(du^*/d\tau\right) = E^*_{u^*}\left(du^*/d\tau\right) > 0$. Therefore, when the regions use emission taxes to control pollution, the Nash equilibrium tax rates are below the rates that maximize the joint welfare. When pollution is local i.e., $\theta = \theta^* = 0$, then the Nash and the cooperative equilibrium emission taxes for both regions coincide, i.e., $\tau^N = \tau^C$ and $\tau^{*N} = \tau^{*C}$.

The following Proposition summarizes the results for the three emission control policies under ICM.

Proposition 5: *Consider two regions with international capital mobility and cross-border pollution. When regions use:*

[13] Contrary to this result, Tsakiris *et al.* (2015) show that when cross-border pollution is perfect, i.e., $\theta = \theta^* = 1$, and regardless of the type of capital mobility, the decentralized setting of inter-regionally tradable emission permits is efficient, i.e., $\left(du/dZ^*_t\right) = \left(du^*/dZ_t\right) = 0$. The difference in the two results is due to the fact that in their framework revenue from sales of tradable emission permits is used to finance public pollution abatement, while in this paper it is lump-sum distributed to households.

- *intra-regionally tradable emission permits, then their Nash equilibrium level is higher than that at the cooperative equilibrium when* $0<\theta,\theta^{*}\leq 1$*, and equal to it when* $\theta,\theta^{*}=0$,
- *inter-regionally tradable emission permits, then their Nash equilibrium level is higher than that at the cooperative equilibrium, regardless of the rate of cross-border pollution,*
- *emission taxes, then their Nash equilibrium rates are smaller than the rates at the cooperative equilibrium when* $0<\theta,\theta^{*}\leq 1$*, and equal to them when* $\theta,\theta^{*}=0$.

The above Proposition indicates that in the presence of cross-border pollution and under ICM, where the rate of return to capital is fixed, irrespectively of whether (i) a region is a capital-importer or exporter, and (ii) which of the three policy instruments it uses, non-cooperative relative to cooperative equilibrium, leads to laxer environmental policy, higher levels of pollution and lower welfare. Under only RCM, where the rate of return to capital is endogenous, (i) this result holds unambiguously for the capital importing region when the environmental policy instrument is inter-regionally tradable emission permits, and for the capital-exporting region irrespectively of the environmental policy instrument used, and (ii) the result may be reversed when the region is a capital-importer and the environmental policy instrument is either intra-regionally tradable emission permits or an emission tax.

4.4 Welfare Ranking of Emission Control Policies under ICM

To provide the welfare ranking of the three emission control policies when regions act non-cooperatively, we again assume that regions are symmetric. Then, the emission control policy regime which at Nash equilibrium leads to a lower overall pollution level, welfare dominates the other two. Under the symmetry assumption equations (27), (29) or (30), and (32), become:

Intra-regionally tradable emission permits: $s_n^N = E_r$, (34)

Inter-regionally tradable permits: $s_t^N = \dfrac{(1+\theta)}{2} E_r$, (35)

Emission taxes: $\tau^N = E_r$. (36)

With ICM and $\theta = 1$, equations (34)-(36) reveal that $s_n^N = \tau^N = s_t^N = E_r$. Pollution levels under the three policy regimes are the same, thus leading to the same levels of welfare. When $0 \le \theta < 1$, then $s_n^N = \tau^N = E_r > s_t^N$. Thus, at Nash equilibrium, pollution is higher and welfare is lower with inter-regionally tradable emission permits, rather than under the other two policy regimes. The following proposition gives the welfare ranking in this case.

Proposition 6: *Consider two symmetric regions with international capital mobility, and cross border pollution. The ranking of the welfare levels* (u) *of the three emission control policies when are chosen non-cooperatively are*

(i) If $\theta = 1$*, then* $u_{Intra-regionally} = u_{Inter-regionally} = u_{Emission\ tax}$.

(ii) If $0 \le \theta < 1$*, then* $u_{Intra-regionally} = u_{Emission\ tax} > u_{Inter-regionally}$.

Comparing the results of the welfare rankings under RCM as given in Proposition 4, with the results under ICM as given in Proposition 6, we state the following Corollary:

Corollary 1: Consider two symmetric regions with cross-border pollution, international or only inter-regional capital mobility, and where intra or inter-regionally tradable emission permits, or emission taxes are used to control pollution. Then, at Nash equilibrium:

(i) $u_{Intra-regionally}^{RCM} = u_{Intra-regionally}^{ICM}$,

(ii) $u_{Inter-regionally}^{RCM} = u_{Inter-regionally}^{ICM}$,

(iii) $u_{Emission\ tax}^{RCM} < u_{Emission\ tax}^{ICM}$.

6. Concluding Remarks

This paper builds a two regions model with capital mobility and production generated cross-border pollution. To control pollution, the two regions use either intra-regionally or inter-regionally tradable emission permits. We examine the cooperative and non-cooperative equilibrium levels of tradable emission permits. We compare the results to the case where the instrument to control pollution is an emission tax, and we provide the welfare ranking of these environmental policy instruments by highlighting the role of the capital mobility regime and of cross-border pollution.

When the regions issue inter-regionally tradable emission permits, the Nash equilibrium level of permits and pollution is higher relative to the cooperative equilibrium. Thus the Nash equilibrium is inefficient relative to the cooperative equilibrium. This results hold for both regimes of capital mobility and for any rate of cross-border pollution.

In the presence of ICM and in the absence of cross border pollution, the Nash and cooperative equilibrium levels of intra-regionally tradable emission permits are equal and thus these policies are equally efficient. This is also true for emission taxes. In the presence of cross-border pollution, however, the Nash equilibrium level of intra-regionally tradable emission permits and emission taxes lead to more pollution and are inefficient relative to the cooperative equilibrium. In the presence of only RCM and in the absence of cross border-pollution, the Nash equilibrium level of intra-regionally tradable emission permits are lower and the emission tax is higher compared to the cooperative equilibrium for the capital importing region. The opposite holds for the capital exporting region. In the presence of cross-border pollution the Nash equilibrium level of intra-regionally tradable emission permits can be either lower or higher and the emission tax can be higher or lower compared to the cooperative equilibrium for the capital importing region. For the capital exporting region the Nash equilibrium level of intra-regionally tradable emission permits is higher and the emission tax is lower compared to the cooperative equilibrium.

In general, at Nash equilibrium, the three policy instruments lead to different levels of pollution and welfare. For example, consider the case of symmetric regions. With only RCM, (i) the Nash equilibrium level of pollution is lower when pollution is controlled via intra-regionally tradable permits as opposed to inter-regionally tradable permits and emission taxes, and (ii) under perfect cross-border pollution, at Nash equilibrium, intra-regionally or inter-regionally tradable emission permits are equally less inefficient to an emission tax, leading to lower levels of pollution and higher welfare. It is only with ICM and perfect cross-border pollution, that at Nash equilibrium all three instruments lead to the same levels of pollution and welfare.

Appendix: Comparative Statics Results

A.I: RCM and Intra-regionally tradable emission permits

Differentiating equations (2), (5) and (6) we obtain the impact of changes in Z_n and Z_n^*, on K and on the intra-regionally tradable permits price s_n and s_n^* as

$$\begin{bmatrix} H_{KK} & R_{Ks_n} & -R^*_{K^*s_n^*} \\ R_{s_nK} & R_{s_ns_n} & 0 \\ -R^*_{s_n^*K^*} & 0 & R^*_{s_n^*s_n^*} \end{bmatrix} \begin{bmatrix} dK \\ ds_n \\ ds_n^* \end{bmatrix} = \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix} dZ_n + \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} dZ_n^* . \tag{A.1}$$

The determinant of the left-hand-side matrix is $\Delta_n = R_{KK} R^*_{s_n^*s_n^*} \tilde{R}_{s_ns_n} + R^*_{K^*K^*} R_{s_ns_n} \tilde{R}^*_{s_n^*s_n^*}$. It is negative since $\tilde{R}_{s_ns_n} = R_{s_ns_n} - R_{s_nK} R_{KK}^{-1} R_{Ks_n} > 0$, $\tilde{R}^*_{s_n^*s_n^*} = R^*_{s_n^*s_n^*} - R^*_{s_n^*K^*} R^{*-1}_{K^*K^*} R^*_{K^*s_n^*} > 0$ and $H_{KK} = R_{KK} + R^*_{K^*K^*} < 0$. From (A.1) we get

$$\left.\begin{array}{l} \dfrac{ds_n}{dZ_n} = \left(-H_{KK} R^*_{s_n^*s_n^*} + R^*_{s_n^*K^*} R^*_{K^*s_n^*}\right)\Delta_n^{-1} < 0, \quad \dfrac{dK}{dZ_n} = R_{Ks_n} R^*_{s_n^*s_n^*} \Delta_n^{-1} > 0, \quad \dfrac{ds_n^*}{dZ_n} = R^*_{s_n^*K^*} R_{Ks_n} \Delta_n^{-1} < 0 \\ \left(dr / dZ_n\right) = \left(dr^* / dZ_n^*\right) = 1, \quad \left(dr / dZ_n^*\right) = \theta, \quad \left(dr^* / dZ_n\right) = \theta^* . \end{array}\right\} \tag{A.2}$$

A.II: RCM and Inter-regionally tradable emission permits

Differentiating equations (2) and (11), we obtain the impact of changes in Z_t and Z_t^* on the permits price s_t and on flows of capital between the two regions as

$$\begin{bmatrix} H_{KK} & \left(R_{Ks_t} - R^*_{K^*s_t}\right) \\ -\left(R_{s_tK} - R^*_{s_tK^*}\right) & -H_{s_ts_t} \end{bmatrix} \begin{bmatrix} dK \\ ds_t \end{bmatrix} = \begin{bmatrix} 0 \\ dZ_t + dZ_t^* \end{bmatrix} . \tag{A.3}$$

The determinant of the right-hand-side matrix is $\Delta_t = -H_{KK} H_{s_ts_t} + (R_{Ks_t} - R^*_{K^*s_t})^2 > 0$. Also, $H_{s_ts_t} = R_{s_ts_t} + R^*_{s_ts_t} > 0$. From (A.3) we get:

$$\frac{ds_t}{dZ_t} = \Delta_t^{-1} H_{KK} < 0 \quad \text{and} \quad \frac{dK}{dZ_t} = -\Delta_t^{-1}\left(R_{Ks_t} - R^*_{K^*s_t}\right) > (<) 0 . \tag{A.4}$$

Using the definitions of r and r^* and the results in (A.4) we have:

$$\frac{dr}{dZ_t} = -\Delta_t^{-1}\left[\left(R_{s_ts_t} + \theta R^*_{s_ts_t}\right)H_{KK} - \left(R_{s_tK} - \theta R^*_{s_tK^*}\right)\left(R_{s_tK} - R^*_{s_tK^*}\right)\right] \text{ and}$$

$$\frac{dr^*}{dZ_t} = -\Delta_t^{-1}\left[\left(R^*_{s_ts_t} + \theta^* R_{s_ts_t}\right)H_{KK} - \left(R^*_{s_tK^*} - \theta^* R_{s_tK}\right)\left(R^*_{s_tK^*} - R_{s_tK}\right)\right]. \tag{A.5}$$

Note that when $\theta = \theta^* = 1$, then $\left(dr / dZ_t\right) = \left(dr^* / dZ_t\right) = 1$.

A.III: RCM and Emission Taxes

When pollution emissions are controlled through emissions taxes, τ for Home and τ^* for Foreign, the system of equations describing the model under capital mobility and cross-border pollution can be written as follows:

$$E(r,u) = R(\tau, K) + \tau z - kR_K(\tau, K)\,, \tag{A.6}$$

$$E^*(r^*,u^*) = R^*(\tau^*, K^*) + \tau^* z^* + kR_K(\tau, K)\,, \tag{A.7}$$

$$z = -R_\tau(\tau, K)\,,\quad z^* = -R^*_{\tau^*}(\tau^*, K^*)\,, \tag{A.8}$$

$$r = z + \theta z^*, r^* = z^* + \theta^* z\,, \tag{A.9}$$

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

The revenue and expenditure functions follow the properties and assumptions described in Section 2. Differentiating equations (A.8) and (A.10) gives

$$\begin{bmatrix} H_{KK} & 0 & 0 \\ R_{\tau K} & 1 & 0 \\ -R^*_{\tau^*K^*} & 0 & 1 \end{bmatrix}\begin{bmatrix} dK \\ dz \\ dz^* \end{bmatrix} = \begin{bmatrix} -R_{K\tau} \\ -R_{\tau\tau} \\ 0 \end{bmatrix} d\tau + \begin{bmatrix} R^*_{K^*\tau^*} \\ 0 \\ -R^*_{\tau^*\tau^*} \end{bmatrix} d\tau^*. \tag{A.11}$$

The determinant of the left-hand-side matrix is $H_{KK} = R_{KK} + R^*_{K^*K^*} < 0$. Thus,

$$\left.\begin{aligned} &\frac{dK}{d\tau} = -R_{K\tau}H_{KK}^{-1} < 0, \frac{dz}{d\tau} = -\tilde{R}_{\tau\tau} < 0, \frac{dz^*}{d\tau} = -R^*_{\tau^*K^*}H_{KK}^{-1}R_{K\tau} > 0 \\ &\frac{dK}{d\tau^*} = R^*_{\tau^*K^*}H_{KK}^{-1} > 0, \frac{dz^*}{d\tau^*} = -\tilde{R}^*_{\tau^*\tau^*} < 0, \frac{dz}{d\tau^*} = \frac{dz^*}{d\tau} > 0 \end{aligned}\right\}, \tag{A.12}$$

where $\tilde{R}_{\tau\tau} = R_{\tau\tau} - R_{\tau K}H_{KK}^{-1}R_{\tau K}$, and equivalently $\tilde{R}^*_{\tau^*\tau^*}$, are positive.

Using equations (17) and (18) the Nash emission taxes are obtained as follows:

$$\left.\begin{array}{l} D_\tau = 0 \Rightarrow \tau^N = E_r + \left(H_{KK}\tilde{R}_{\tau\tau}\right)^{-1} R_{\tau K}\left(\theta E_r R^*_{\tau^* K^*} - kR^*_{K^*K^*}\right) \\ D^*_{\tau^*} = 0 \Rightarrow \tau^{*N} = E^*_{r^*} + \left(H_{KK}\tilde{R}^*_{\tau^*\tau^*}\right)^{-1} R^*_{\tau^* K^*}\left(\theta^* E^*_{r^*} R_{\tau K} + kR^*_{K^*K^*}\right) \end{array}\right]. \tag{A.13}$$

A.IV Proof of Proposition 3

For the capital importing region we proceed as follows. At Nash equilibrium,

$$E^*_{u^*}\frac{du^*}{d\tau^*} = D^*_{\tau^*} = 0 \Rightarrow (E^*_{r^*} - \tau^*) = -\left(\theta^* E^*_{r^*} R^*_{\tau^* K^*} + kR^*_{K^*K^*}\right)\left(H_{KK}\tilde{R}^*_{\tau^*\tau^*}\right)^{-1} R_{K\tau} > 0. \tag{A.14}$$

Substituting equation (A.14) into the expression for $E^*_{u^*}\left(du^* / d\tau\right)$ in equation (20), we obtain the result stated in the Proposition. Similarly, for the capital exporting region using the Nash equilibrium conditions we obtain:

$$E_u \frac{du}{d\tau} = D_\tau = 0 \Rightarrow (E_r - \tau) = -\left(\theta E_r R^*_{K^*\tau^*} - kR^*_{K^*K^*}\right)\left(H_{KK}\tilde{R}_{\tau\tau}\right)^{-1} R_{K\tau} > (<) 0. \tag{A.15}$$

Substituting (A.15) into the expression for $E_u\left(du / d\tau^*\right)$ in equation (19) we obtain:

$$E_u \frac{du}{d\tau^*} = \theta E_r\left[\tilde{R}^*_{\tau^*\tau^*} - \left(H_{KK}\tilde{R}_{\tau\tau}\right)^{-1} R^2_{\tau K} H^{-1}_{KK} R^{*2}_{K^*\tau^*}\right] + kR_{\tau K} R^*_{K^*K^*} H^{-1}_{KK}\left[-1 + \left(H_{KK}\tilde{R}_{\tau\tau}\right)^{-1} R_{\tau K} R^*_{K^*\tau^*}\right]. \tag{A.16}$$

The sign of the second right-hand-side term in equation (A.16) is positive, while that of the first term appears ambiguous. Some further algebra, however, shows that:

$$\theta E_r\left[\tilde{R}^*_{\tau^*\tau^*} - \left(H_{KK}\tilde{R}_{\tau\tau}\right)^{-1} R^2_{\tau K} H^{-1}_{KK} R^{*2}_{K^*\tau^*}\right] = \theta E_r \tilde{R}^*_{\tau^*\tau^*}\left(1 - \Omega\right) > 0,$$

where $0 < \Omega = \dfrac{R^2_{\tau K} R^{*2}_{K^*\tau^*}}{\left(R^2_{\tau K} - H_{KK} R_{\tau\tau}\right)\left(R^{*2}_{K^*\tau^*} - H_{KK} R^*_{\tau^*\tau^*}\right)} < 1$. Subsequently, evaluated at Nash equilibrium values, $E_u\left(du / d\tau^*\right) > 0$, hence for the capital exporting region $\tau^{*N} < \tau^{*C}$.

References

Antoniou, F., P. Hatzipanayotou and P. Koundouri, 2014, Tradable permits vs. ecological dumping when governments act non-cooperatively, Oxford Economics Papers 66, 188-208.

Chen, X. and A. Woodland, 2013, International trade and climate change, International Tax and Public Finance 20, 381-413.

Copeland, B., and M.S. Taylor, 1995, Trade and transboundary pollution, American Economic Review 85, 716-737.

Copeland, B., and M.S. Taylor, 2005, Free trade and global warming: a trade theory view of the Kyoto protocol, Journal of Environmental Economics and Management 49, 205-234.

--------------, 2004, Trade, growth, and the environment, Journal of Economic Literature 42, 7-71.

Dijkstra, B.R. Manderson, E., and T-Y. Lee, 2011, Extending the sectoral coverage of an international emission trading scheme, Environmental and Resource Economics 50, 243-266.

Eichner, T. and M. Runkel, 2012, Interjurisdictional spillovers, decentralized policymaking, and the elasticity of capital supply, American Economic Review 102, 2349-2357.

Ellerman, D., P. L. Joskow and D. Harrison, 2003, Emissions trading: Experience, lessons, and considerations for greenhouse gases, Pew Center on Global Climate Change, Washington, D.C.

Ellerman, D. and P. L. Joskow, 2008, The European Union's emissions trading system in perspective, Policy, Pew Center on Global Climate Change, Washington, D.C.

Fell, H. and D.T. Kaffine, 2014, Can decentralized planning really achieve first-best in the presence of environmental spillovers?, Journal of Environmental Economics and Management, forthcoming.

Hadjiyiannis C., Hatzipanayotou, P., and M.S. Michael, 2009, Public pollution abatement, regional capital mobility, and tax competition, Southern Economic Journal 75, 703-719.

Helm, C., 2003, International emissions trading with endogenous allowance choices, Journal of Public Economics 87, 2737-2747.

Jouvet, P-A. and G. Rotillon, 2012, Capital accumulation and international equilibrium with pollution permits, Modern Economy 3, 187-199.

Kotsogiannis, C. and A. Woodland, 2013, Climate and international trade policies when emissions affect production possibilities, Journal of Environmental Economics and Management 66, 166-184.

Lapan, H. and S. Sikdar, 2011, Strategic environmental policy under free trade with transboundary pollution, Review of Development Economics 15, 1-18.

Mæstad, O., 2007, Allocation of emission permits with leakage through capital, Resource and Energy Economics 29, 40-57.

----------------------, 2006, Environmental policy and public revenue with international capital mobility, International Tax and Public Finance 13, 43-58.

Malueg, D. and A. Yates 2009, Strategic behavior, private information, and decentralization in the European Union Emissions Trading Scheme, Environmental and Resource Economics 43, 413-432.

Neary, J.P., 2006, International trade and the environment: Theoretical and policy linkages, Environmental and Resource Economics 33, 95-118.

Norrengraad, J. and V. Reppelin-Hill, 2000, Controlling pollution: Using taxes and tradable permits, Economic Issues no 25, IMF, Washington D.C.

Oates, W. and R. Schwab, 1988, Economic competition among jurisdictions: Efficiency enhancing or distortion inducing?, Journal of Public Economics 35, 333-354.

Ogawa, H. and D. Wildasin, 2009, Think locally, act locally: Spillovers, spillbacks and efficient decentralized policy making, American Economic Review 99, 1206-1217.

Petchey, J., 2014, Environmental standards in a large open economy, Journal of Public Economic Theory, forthcoming.

Tsakiris, N., P. Hatzipanayotou, and M.S. Michael, 2015, Emission permits and public pollution abatement: Can decentralized environmental policies be efficient, CESifo Working Papers Series, no. 5278, CESifo-Munich.