THESIS: ASPECTS OF PARETO IMPROVING ENVIRONMENTAL TAX REFORMS

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

‘Climate change is the greatest and widest-ranging market failure ever seen’ Stern (2006 p. xvii). This vigorous description highlights one of the most important and frustrating realization of the last decades. The main reason of that market failure steams from the fact that climate change is a complex global externality. This makes the design of appropriate measures to mitigate the problem and the identification of their effects on economic activity of paramount importance. The transboundary nature of pollution combined with the skewed distribution of the origin and impact of emissions among countries reveals the need for international cooperation in the direction of multilateral agreements among countries.

The characterization of Pareto-efficient environmental and trade policies has been a key issue (and continues to be) in the literature. Predominantly, however, the literature has focused on the role of taxes (trade and pollution) in achieving the first-best paying no attention to the role (if there is any) of non-tradeable goods. Chapter 4 deals with this issue.

A key issue in mitigating climate change is with the appropriate extent of harmonization of environmental policies. This thesis (Chapters 2) addresses this within a general equilibrium model of international trade with endogenous pollution discharges, paying particular attention to the allocation of tax revenues. It argues that there indeed exist instances in which pollution tax harmonization (that moves the initial pollution taxes towards an appropriately weighted pollution tax vector) can deliver potential Pareto improvements.

The difficulty with the achievement of global environmental agreements should not be, however,

ignored. Chapter 3 deals with the possibility that governments may act unilaterally in order to mitigate the social cost of pollution. It shows that (under certain conditions) there exist unilateral Pareto improving trade policy reforms. Chapter 5 discusses the welfare implication of environmental policy reforms within a subset of countries. It shows that environmental policy coordination has opposing effect on the welfare of the coordinating and non-coordinating countries.

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Chapter 1 Introduction

Climate change is considered as one of the most challenging issues currently facing the world. There is an increasing consensus—supported also by some compelling evidence[1]—that a significant portion of the average increase in global temperature is caused by emissions of greenhouse gases (especially carbon dioxide) as a consequence of increased economic activity. Clearly, if such tendency continues the stock of greenhouse gases, which dissipates very slowly, in the atmosphere is expected to alter climate substantially, and in many different ways, with serious, and possibly catastrophic, effects on the welfare of future generations.

Climate change, in economic terms, is a global externality: Emitting countries ignore the damage they cause to others, thereby emitting more than it is desirable from a global perspective.[2] But it is a particularly complex externality given the asymmetric impact of the stock of emissions on the geographical distribution and economic activity. Given the global nature of the externality international cooperation is required. And this is the objective of the thesis. More specifically, the thesis—in broad terms—asks to what extent (given the transboundary nature of emissions—and within a setup in which countries trade in goods) do there exist Pareto-improving carbon-tax reforms? It shows that—under certain conditions and in a variety of different modelling frameworks—they do exist.

The literature (both theoretical and empirical) on the nexus of international trade and climate

[1] Stern (2006) provides some discussion on the evidence and the science of climate change.

[2] Climate change is caused by the collective action problem: A unilateral reduction in emissions by one country reduces the marginal benefit of abatement to others thereby increasing their incentive to abate less.

change is fairly sizeable,[3] and has paid attention to the characterization of both non-cooperative policies—as in, for instance, Baumol and Oates (1988) and Markusen (1975)—and the cooperative ones (Pareto efficiency)—as in, for instance, Keen and Kotsogiannis (2012). I do not wish to repeat the results of the thesis here, but it will be, I think, informative for the reader if I put the thesis into perspective. This, however, requires an introduction to the issues, and this the objective of this chapter.

The rest of this chapter is organized as follows: Section 1.1 introduces the standard model of international trade (analyzed in more detail in the subsequent chapters) that accounts for pollution externalities affecting consumers through utility (or factor endowments). Section 1.2 identifies important welfare effects and discusses first- and second-best optimal levels of pollution and trade policies, in the presence of either taxes or (for completeness) quantitative restrictions. Section 1.3 discusses some of the key policy issues in the interaction between trade and environmental policies. Section 1.4 focuses on the welfare effects of environmental and trade policy reforms, and finally Section 1.5 concludes.

1.1 Description of the model

This section develops a simple model—that, as noted above, will also be used in the subsequent chapters[4]—that incorporates environmental constraints into an international trade model. This model will serve as a theoretical framework for the discussion on the interaction of trade and environmental policies.

The framework is a perfectly competitive general equilibrium of international trade with two small open economies (conveniently labelled 'home' and 'foreign') with their variables indexed by the super-

[3] For early contributions—discussing the consequences of pollution externalities on economic activity—see Baumol (1971) and Markusen (1975). Recent insightful surveys are by Copeland and Taylor (2004) and Chen and Woodland (2012).

[4] Chapter 2 extends this model to many countries.

script 1 and 2, respectively. In each country there is a private sector (with a representative identical consumer) that produces N tradable[5] commodities with their international prices—denoted by w—treated (for the purpose of this section) as fixed. The first traded commodity is chosen as the numeraire good, with its home and foreign prices being normalized to unity. It will also be assumed throughout that the numeraire good is subject to no restrictions.

Production of the N goods in each country generates some pollutant. Pollution is, therefore, modeled as a by-product of production and its level of output in country j is denoted by the N-vector z^j. Total emissions generated by the production in each country j are given by $i'z^j$, where i is the N-vector of $1s$. The effects of pollutants can either be local—and so the stock of emissions is equal to the emissions produced in that country—or global in which case it is given by[6]

$$k = \sum_{j=1}^{2} i'z^j \ . \tag{1.1}$$

The theoretical literature addressing the linkage of climate change and economic activity has identified two *direct* welfare effects of pollution; one on consumers' utility and the other on country's endowments. Predominately, however, attention has been paid to the effects of pollution on consumers' utility (as in, for example, Baumol and Oates (1988), Markusen (1975), Copeland (1994), Copeland and Taylor (1994, 1995), Turunen-Red and Woodland (2004) and Keen and Kotsogiannis (2012)), with less attention being paid to the effects of pollution on a country's endowments (Copeland and Taylor (1999) Benarroch and Thille (2001) and Kotsogiannis and Woodland (2012)). Though this distinction is interesting from a

5 Chaper 4 introduces non-tradeable goods. For presentation purposes these goods will not feature here.

6 One can also introduce a parameter θ^j that captures the magnitude of the externality from the foreign (home) to the home (foreign) country. For simplicity, it will be assumed that $\theta^j = 1$.

theoretical point of view it is of no importance for what follows. Consequently, and for ease of comparison across the many results in the literature, the exposition will focus on the effects of emissions through utility.

Consider consumer preferences (represented by the expenditure function) in country j

$$e^j(p^j, u^j, k) = \min_x \left\{ p^{j\prime} x^j : u^j \left(x^j, k \right) \geq \bar{u}^j \right\} \ . \tag{1.2}$$

Equation (1.2) gives the minimum expenditure required to achieve utility $\bar{u}^j$ given pollution k and prices p^j (the expenditure function is concave and linearly homogeneous in prices, increasing in utility, and assumed to be twice continuously differentiable). The consumer's compensated demand is defined, as an envelope property, by the vector e^j_p, while e^j_k represents the consumer's marginal willingness to pay for pollution reduction and, hence, the marginal damage caused by pollution. The expenditure function is (assumed) increasing in k since an increase in the level of any pollutant requires an increase in consumption to compensate the consumer for the extra pollution, that is $e^j_k > 0$.

The private sector is characterized by a revenue function which has the properties of a restricted profit function.[7] The revenue function is denoted by

$$r^j(p^j, v^j) = \max_y \{ p^{j\prime} y^j : (y^j) \in T^j(v^j) \} \ , \tag{1.3}$$

where $T^j(v^j)$ is the technology set given the vector of factor endowments v^j.

The vector of (net) output of tradeable goods is denoted by y^j and given, following Hotelling's

[7] For the properties of the revenue function see Dixit and Norman (1980) and Woodland (1982).

lemma, by $y^j = r^j_p(p,s)$. The revenue function is convex, linearly homogeneous and assumed to be twice continuously differentiable.[8]

1.2 Environmental and trade policy

Two types of policy instruments, in general, can be used to implement environmental and trade policies:[9] *carbon taxes* (or—equivalently[10]—*quantitative restrictions* on the production of carbon) and *trade taxes* (with prices determined endogenously and the terms of trade mechanism in place).[11] With each instrument directly affecting its corresponding economic sector (trade taxes affect trade flows whereas emission taxes affect emissions), it is intuitive that the first best optimal policy requires the use of two policy instruments; carbon taxes targeting the externality directly with trade taxes affecting the flow of trade.[12] Under second-best optimal policy, however, either there is only one policy instrument available, or there are two but they have been set at inefficient levels.[13]

1.2.1 Environmental and trade taxes

Suppose that each country j imposes sector specific pollution taxes, s^j, and import taxes/subsidies,

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8 Notice, for completeness, the revenue function when pollution affects effective endowments is given by

$$r^j(p^j, v^j(k)) = \max_y\{p^{j\prime} y^j : f^j(y^j, v^j(k)) \leq 0\} ,$$

where k is still defined by (1.1). For more on this see Kotsogiannis and Woodland (2012).

9 Carbon taxes and pollution taxes are used interchangably to mean the same policy instrument.

10 Equivalent, that is, in perfectly competitive environments.

11 Notice that this is not the case of this chapter as it focuses on small open economies.

12 This is reminiscent of the ‘targeting principle’: Since there are pontetially two inefficiencies, one in the production of emissions and one in the pattern or trade, the ‘targeting principle’ requires that optimal policy is implemented with two instruments (trade and carbon taxes) that targets the two corresponding ineffciencies.

13 For contributions see, among others, Markusen (1975), Baumol and Oates (1988), Krutilla (1991) Hoel (1996),Copeland (1994)(2000), Beghin et al. (1997), Ulph (1997), Lubema and Wooton (1994), (1997), Neary (2006), Antoniou et al. (2010) and Keen and Kotsogiannis (2012).

t^j. Suppose further that pollution and trade tax revenues collected by the government are returned to the consumer in a lump-sum fashion.[14] The private sector's revenue function is given by

$$r^j(p^j, s^j, v^j) = \max_y \{p^{j\prime} y^j - s^{j\prime} z^j : (y^j, z^j) \in T^j(v^j)\} \;, \tag{1.4}$$

with the vector of emissions being given—as an envelope property from (1.4)—by

$$z^j = -r_s^j \,(p, s) \;\; . \tag{1.5}$$

The consumer's expenditures are equal to GDP, given by (1.4), plus the pollution tax and tariffs revenues and so the budget constraint for the consumer is given by

$$e^j \left(u^j, k, p^j\right) = r^j \left(p^j, s^j\right) + t^{j\prime} \left(e_p^j \left(u^j, k, p^j\right) - r_p^j \left(p^j, s^j\right)\right) + s^{j\prime} z^j \; . \tag{1.6}$$

where

$$p^j = w + t^j \; . \tag{1.7}$$

Perturbing (1.1), after making use of the fact that—following $dw = 0$—$dp^j = dt^j$, one obtains

$$dk = -\sum_{j=1}^{2} i^\prime (r_{sp}^j dt^j + r_{ss}^j ds^j) \;, \tag{1.8}$$

which simply says that pollution, in each country, is affected by how the production sector responds to the environmental and trade policies.

To characterize Pareto efficient pollution taxes and tariffs for country 1, perturb (1.6), making use

14 Tax revenues can be also used for public abatement. Chapter 2 explores this possibility.

of (1.8) and $dp^j = dt^j$, to obtain

$$e_u^1(1 - t^{1\prime}m^1)du^1 = \left[\left(e_k^1 i' - t^{1\prime}e_{pk}^1 i' - s^{1\prime}\right) r_{sp}^1 - t^{1\prime}\lambda^1\right] dt^1 + \left[\left(e_k^1 i' - t^{1\prime}e_{pk}^1 i' - s^{1\prime}\right) r_{ss}^1 - t^{1\prime}r_{ps}^1\right] ds^1 + \left(e_k^1 - t^{1\prime}e_{pk}^1\right) i' r_{sp}^2 dt^2 + \left(e_k^1 - t^{1\prime}e_{pk}^1\right) i' r_{ss}^2 ds^2 \ , \tag{1.9}$$

where $1 - t^{1\prime}m^1 > 0$, with $m^1 = e_{pu}^1/e_u^1$, and $\lambda^1 = r_{pp}^1 - e_{pp}^1$ is a positive semi-definite matrix of country 1's excess compensated supplies.[15,16] Equation (1.9) defines the optimal policies for country 1. It is easy to show that, for a small open economy, the first best policy is free trade, that is[17]

$$t^j = 0 \ \ j = 1, 2 \ , \tag{1.10}$$

and pollution taxes equal to the consumer's marginal damage from pollution, that is

$$e_k^j i = s^j \ \ j = 1, 2 \ . \tag{1.11}$$

I turn now to the characterization of the second-best optimal policy when either of these policy

[15] The parameter $e_u\left(1 - t'm\right)$ deflates the real income by the tariff multiplier, Neary (2006). It also relates to the stability of the equilibrium.

[16] Welfare changes in country 2 is given by

$$e_u^2(1 - t^{2\prime}m^2)du^2 = \left[\left(e_k^2 i' - t^{2\prime}e_{pk}^2 i' - s^{2\prime}\right) r_{sp}^2 - t^{2\prime}\lambda^2\right] dt^2 + \left[\left(e_k^2 i' - t^{2\prime}e_{pk}^2 i' - s^{2\prime}\right) r_{ss}^2 - t^{2\prime}r_{ps}^2\right] ds^2 + \left(e_k^2 - t^{2\prime}e_{pk}^2\right) i' r_{sp}^1 dt^1 + \left(e_k^2 - t^{2\prime}e_{pk}^2\right) i' r_{ss}^1 ds^1 \ .$$

[17] Prices satisfy $p^1 = p^2$ and so there is production efficiency from a global perspective.

instruments is not available. In this case the available policy instrument should take account both the trade and environmental impacts on welfare.

Equation (1.9) suggests that in the absence of tariffs country 1's non-cooperative level of pollution taxes continues to be $e_k^1 i = s^1$. Indeed this is the case. To see this, set $t = 0$ and $dt^1 = ds^2 = dt^2 = 0$ in (1.9) to obtain

$$e_u^1 du^1 = \left(e_k^1 i' - s^{1\prime}\right) r_{ss}^1 ds^1 \ . \tag{1.12}$$

In the absence of pollution taxes the optimum level of country 1's tariffs is given by

$$t^{1\prime} = e_k^1 i' r_{sp}^1 (e_{pk}^1 i' + \lambda^1)^{-1} \ , \tag{1.13}$$

assuming that the matrix $e_{pk}^1 i' + \lambda^1$ is invertible. Clearly, free trade is not an optimal trade policy when pollution taxes are not available (see Markusen (1975)).

To summarize, the first- and second-best non-cooperative optimal environmental policy—in a small open economy—requires the government set its environmental taxes equal to the consumers marginal willingness to pay for pollution reduction. In contrast, the first- and second-best non-cooperative optimal trade policies do not coincide. For completion we now turn to the analysis of the first- and second-best non-cooperative optimal environmental and trade policy under quantitative restrictions.

1.2.2 Environmental and trade quantitative restriction

Suppose now that each country employs quantitative restrictions on trade and pollution. As in Copeland (1994), it is assumed that the government issues pollution permits that are marketable and fixed in supply, z^j. The (shadow) prices of permits are given by the N-vector s^j. Assume also that imports are subject to binding quotas M^j.[18] The revenue function is now given by

$$r^j(p^j, z^j, v^j) = \max_y \{p^{j\prime} y^j : (y^j, z^j) \in T^j(v^j)\} \ . \tag{1.14}$$

The equilibrium is defined by ($j = 1, 2$)

$$e^j\left(u^j, k, p^j\right) = r^j\left(p^j, z^j\right) + t^{j\prime} M^j \ , \tag{1.15}$$

$$M^j \equiv e^j_p - r^j_p \ , \tag{1.16}$$

$$t^j = p^j - w^j \ , \tag{1.17}$$

$$k = \sum_{j=1}^{2} i' z^j \ . \tag{1.18}$$

Equation (1.15) represents the consumer's budget constraint. Notice that, in contrast to the case where environmental taxes are available (see equation (1.6)), now there are no revenues from pollution going back to the consumer as governments do not sell these permits to firms. Import-binding quotas, M^j, are given exogenously but their domestic price is determined endogenously by (1.16) and (1.17). Finally, equation (1.18) gives the global pollution level which is equal to the sum of the pollution permits issued by both governments.

To derive the Pareto efficient policies, perturb equation (1.15), making use of $dk = \sum_{j=1}^{2} i' dz^j$ and $dp^j = dt^j$, to obtain

$$e^1_u du^1 = \left(r^{1\prime}_z - e^1_k i'\right) dz^1 + t^{1\prime} dM^1 - e^1_k i' dz^2 \ . \tag{1.19}$$

18 As before, any revenues collected by the government are returned to the consumer in a lump-sum fashion.

Notice that in contrast to the previous case—see equation (1.9)—in which imports and pollution levels were affected indirectly by taxes, now the distortions of the control variables do not impose any indirect effect on country 1's welfare. To put it differently, equation (1.19) simply shows that the country 1's welfare is affected only directly by the environmental and trade policy distortions. The terms inside the parentheses—$(r_z^{1\prime} - e_k^1 i')$—give the effects on country 1's welfare driven by the distortion of its pollution permits, that is measured by the deviation of permit-prices from the marginal damage of pollution. The second term, $t^{1\prime} dM^1$, represents the effect on country 1's welfare driven by the changes on imports quotas.[19] Finally, the last term, $-e_k^1 i' dz^2$, gives the cross country effect in country 1 driven by changes in country 2's environmental policy.

Equation (1.19) suggests that the first- and second-best optimal policies are the same, as in the case where price instruments are used. The reason for this is intuitive: quotas affect only trade flows and pollution permits affect only the level of pollution. Overall, the optimal environmental policy for the government is to set the pollution permits equal to the marginal damage from pollution and to impose no restrictions on imports.

1.2.3 Cooperative environmental and trade policy

As noted in the introductory section, the transboundary nature of pollution combined with the skewed distribution of the origin and impact of emissions among countries calls for international cooperation. If a country's contribution to global pollution is large, and its perceived marginal damage is sufficiently low, it will be in its interest to under-tax its polluting activities. Thus, each country act-

[19] The term $t^{1\prime} dM^1$ can be split into the terms of trade effect given by $t^{1\prime} M_p dp$—note that this term is absent in this case as it focusses on small open economies—and the revenues collected by the government given by $t^{1\prime} M_p dt$.

ing strategically will set its environmental policy for its own benefit and so environmental taxes set in a non-cooperative manner will be too low from a global perspective.

To derive the cooperative allocations combine equation (1.9) with the corresponding one for country 2 to obtain[20]

$$\begin{aligned}\sum_{j=1}^{2} e_u^j(1-t^{j\prime}m^j)du^j &= \left[\left(e_k^1 i' + e_k^2 i' - s^{1\prime} - t^{1\prime}e_{pk}^1 i' - t^{2\prime}e_{pk}^2 i'\right) r_{sp}^1 - t^{1\prime}\lambda^1\right] dt^1 \\ &+ \left[\left(e_k^2 i' + e_k^1 i' - s^{2\prime} - t^{2\prime}e_{pk}^2 i' - t^{1\prime}e_{pk}^1 i'\right) r_{sp}^2 - t^{2\prime}\lambda^2\right] dt^2 \\ &+ \left[\left(e_k^1 i' + e_k^2 i' - s^{1\prime} - t^{1\prime}e_{pk}^1 i' - t^{2\prime}e_{pk}^2 i'\right) r_{ss}^1 - t^{1\prime}r_{ps}^1\right] ds^1 \\ &+ \left[\left(e_k^2 i' + e_k^1 i' - s^{2\prime} - t^{2\prime}e_{pk}^2 i' - t^{1\prime}e_{pk}^1 i'\right) r_{ss}^2 - t^{2\prime}r_{ps}^2\right] ds^2 \ .\end{aligned} \tag{1.20}$$

Taking the derivatives of (1.20) with respect to s^j and t^j, and solving simultaneously the first order conditions, one obtains the fist best optimum levels given by

$$s^j = e_k^1 i + e_k^2 i > 0 \quad \text{and} \quad t^j = 0 \quad j = 1, 2 \ . \tag{1.21}$$

Pareto efficiency, therefore, dictates free trade and uniform pollution taxes within and across countries. If now quantitative restrictions for trade and environmental policy are allowed, global *welfare* is given by

$$\sum_{j=1}^{2} e_u^j du^1 = \left(r_z^{1\prime} - e_k^1 i' - e_k^2 i'\right) dz^1 + \left(r_z^{2\prime} - e_k^2 i' - e_k^1 i'\right) dz^2 + t^{1\prime}dM^1 + t^{2\prime}dM^2 \ . \tag{1.22}$$

In this case, too, Pareto efficiency dictates free trade and the shadow price of the pollution permits

[20] Implicitly, behind this is the existence of lump sum transfers between countries.

to be uniform across and within countries and equal to the damage caused by the marginal emission.

Matters are, however, different if countries are ‘large open economies’. Markusen (1975) was the first to deal with first- and second-best optimum policies in the presence of pollution externalities, focusing on large open economies. Markusen (1975) developed a model with two countries, two goods and production, consumption and trade taxes.[21] Within such model he identified the firs-best optimum policy level. He, then, analyses the case is which only one policy instrument is available, showing how a limited number of instruments can deal with several distortions simultaneously. Markusen (1975) argued that the ranking of second best tax structures depends upon which good is imported and which good is exported.

Krutila (1991) focused on the second-best optimum level of environmental taxes in the presence of either production or consumption externalities, showing that environmental taxes should be modified to account for the terms of trade effect, unless trade policy is available.

More recently, Keen and Kotsogiannis (2012) and Kotsogiannis and Woodland (2012), using a more general approach, characterize Pareto optimal policies for large open economies—with and without lump sum transfers—when climate change affects consumers (Keen and Kotsogiannis (2012)) or factor endowments (Kotsogiannis and Woodland (2012)). Keen and Kotsogiannis (2012) discuss the issue of environmental and trade policy for large open economies, including border tax adjustments. They argue that Pareto optimality requires that when lump sum transfers are available environmental taxes take a Pigouvian form and they are uniform within and across the countries. Tariffs are the same across

[21] No environmental policies are available.

countries—and so there is production efficiency—but redundant and they can be normalized away. Pareto efficient trade policy is characterized by free trade. When lump sum transfers are not available, environmental taxes take a Pigouvian-adjusted form and they are the same within countries but different across countries. In this case suggesting that they should be set lower in the income needy countries. Pareto efficiency requires that carbon taxes explicitly take into account the cost of abatement (and relative to the distribution of income across countries), whereas trade policy explicitly takes into account any need for redistribution of income across countries. These results remain unchanged if pollution affects effective endowments, Kotsogiannis and Woodland (2012).[22]

1.3 Environmental and trade policy interactions

Having discussed the different aspects of environmental and trade policies and their first- and second-best optimum allocations, I now turn to some of the key policy issues. This section asks whether trade liberalization will cause countries with relatively weak environmental policy to specialize in the production of pollution intensive goods.

1.3.1 Pollution haven effect

A key issue of the literature is the effects of environmental policy on the international competitiveness of firms: The idea being whether tighter environmental regulation lowers or raises international competitiveness of pollution intensive industries. This is known as the *pollution haven effect* or *compet-*

[22] Although these results are insightful they have ignored a really important economic feature: non-tradeable goods. This is the focus of Chapter 4. Relaxing this assumption, and allowing for non-tradable goods, Chapter 4 characterizes Pareto-efficient environmental and trade policies. It reconfirms the result of Keen and Kotsogiannis (2012), showing that in the presence of lump sum taxes Pareto optimality requires carbon taxes to be uniform across countries (and within each country) including the sectors of non tradable goods. While in the absence of lump sum taxes, they are uniform within each country but not across all countries.

itiveness hypothesis. In terms of the model presented—and in particular equation (1.4)—the hypothesis relates to the pollution intensity of, say, good i. If

$$r_{ps}^{i} = \frac{\partial y^{i}}{\partial s} \leq 0 \; , \tag{1.23}$$

then tightening pollution regulation decreases the production of pollution intensive goods. This argument has gained some support both theoretically and empirically. Whalley and Whitehead (1994), for instance, argue that any gains from pollution reduction will be offset by the losses of domestic industries. This view has been challenged by Porter (1991) and Porter and van der Linde (1995) who put forward a hypothesis that is now know as the Porter hypothesis. The Porter hypothesis, states that in the long run stricter environmental regulation will improve the competitiveness of polluting sectors. This could be possible if tighter environmental regulation may force firms to realize their polluting behavior and redesign their production process in a more efficient manner. Another argument in favor of the Porter hypothesis is that tighter environmental regulation may motivate firms to develop or adopt newer and cleaner technologies in order to increase their competitiveness in world markets. This argument could be supported if governments subsidize their domestic firms to innovate.[23] In contrast to the pollution haven effect, if pollution is generated by consumption tighter environmental regulation will not affect the firms' competitiveness. The reason for this is that environmental regulations target all goods consumed within

[23] Early works on this issue provides little or no evidence in favor of the pollution haven effect (see among others Walter (1973), Levinson (1996) and Jaffe et al.(1995)). This work argues that the abatement cost is only a small fraction of the overall production cost. The main criticism on this work is the use of cross-sectional data. This view has been challenged within the last decade as more international data became available. See, among others, Ederington and Minier (2003) and Levinson and Taylor (2008) who use methods that account for the endogeneity of environmental policy and find support for the pollution haven effect. Greaker (2006) also provides empirical evidence in support of the Porter hypothesis. See also Becker and Henderson (2000) and List et al. (2003).

the regulated country, and, hence they affect both domestically produced and imported goods.

1.3.2 Pollution haven hypothesis

Pollution haven hypothesis is defined as the reallocation of pollution intensive industries to countries with relatively weaker environmental policies due to trade liberalization. This implies that countries with weaker environmental regulations will specialize in the production of pollution intensive goods, consequently these countries will become the exporters of such goods.[24] The condition for the pollution haven hypothesis to hold is that the competitiveness hypothesis holds and the abatement cost of firms,is a high fraction of the overall production cost.

Pethig (1976) was the first to provide a theoretical analysis of the pollution haven hypothesis. Employing a Ricardian trade model with exogenous and different environmental policy across countries he showed that the country with weaker environmental policy will be the exporter of pollution intensive goods. Levinson and Taylor (2008), using exogenous environmental policies in a model with a continuum of industries, argue that differences among countries in the levels of emission taxes will affect the allocation of firms. In support of the pollution haven hypothesis, they showed that the country with the weaker environmental policy will specialize in the production of the most pollution intensive goods. Although these studies provide significant support for the pollution haven hypothesis they treat environmental policy as exogenously which is rather restrictive. As pointed out by Grossman and Krueger (1995), and more recently by Copeland (2005), if environmental policy is exogenous, then income affects environmental quality only indirectly through changes in environmental policy.

[24] This issue has generated a heated debate between environmentalists and economists. There has been a fairly sizeable literature that tries to verify (or refute) this hypothesis, but the results are still inconclusive.

Copeland and Taylor (1994) develop a model with endogenous environmental policy. They consider an economy consisted of two countries, North and South, with North being richer and setting stricter environmental policy, since environmental quality is a normal good. They also assume a continuum of goods[25] that differs in their pollution intensity of production. They model pollution taxes as an endogenous choice of governments. Copeland and Taylor (1994) decompose the effects of trade liberalization and pollution policy into: a) *scale*, b) *technique* and c) *composition effects*. The scale effect is defined as the effect on pollution level caused by an increase in the level of economic activity. The technique effect measures the effect on pollution, arising from a switch in production to less pollution intensive techniques. The composition effect reflects the changes in the range of goods produced in a country. They show that under free trade the South—poor country—specializes in the production of the most pollution intensive goods. The implication of this is that—since the most polluting industries shift to the country with the less restrictive environmental policy—global pollution increases. Copeland and Taylor (1995) extend this analysis by also allowing for transboundary pollution. They predict that under free trade, and when factor price equalization occurs, the pollution hypothesis will hold but global environmental quality will be unaffected as free trade has no effect on global emissions. This, however, ceases to hold when factor price equalization is not the equilibrium outcome as the North chooses higher pollution taxes thereby increasing global pollution.

Even if theory provides evidence in favor of the pollution haven hypothesis empirical studies do not provide unambiguous support. Antweiler, Copeland and Taylor (2001) find evidence that trade increases

[25] In line of the Dornbusch et al. (1977) model.

pollution in rich countries relatively to the poor ones. They argue that the lack of support of their result for the pollution haven hypothesis lies on the contradicting effects of environmental policy and capital abundance. This view is supported by the findings of Frankel and Rose (2005) and Cole and Elliott (2003) who estimate the composition effects of trade liberalization.

The main reason for the lack of empirical evidence of the pollution haven hypothesis is that other factors rather than the environmental policy may affect the reallocation decision of firms (see Grossman and Krueger (1993)), such as agglomeration economies and transportation costs.[26]

1.3.3 Environmental policy responses to trade liberalization

The previous discussion was based on the premise that environmental policies remain unchanged as trade liberalization occurs. This section relaxes this assumption focusing on the effect of trade liberalization on environmental policy.

In the absence of appropriate instruments (trade taxes) governments may have the intensive to use environmental policy to protect local industries, following trade liberalization This policy substitution holds if trade liberalization is expected to jeopardize the competitive position of domestic industries through either losses in market share or reallocation of these industries to countries with weaker environmental policies.

Environmental policy may also affect directly the terms of trade. In the absence of trade restrictions, governments could use environmental policy as a second-best trade policy. If the country is the

[26] For more detailed discussion on the factors that affect the reallocation of firms see Copeland and Taylor (1997) and Richelle (1996). Also Zeng and Zhao (2009) and Wagner and Timmins (2009) highlight the effect of agglomeration, providing evidence that contradict the pollution haven hypothesis.

exporter of the pollution intensive goods, then tighter environmental policy will improve its terms of trade as it will increase the price of these goods. In contrast, if the country specializes in the production of clean goods then tighter environmental taxes will deteriorate its terms of trade.

Trade liberalization might also induce changes in environmental policy through ‘emissions leakages’. A country’s environmental policy can have an impact on the foreign country’s emissions. This, combined with the global nature of pollution, may result in an increase in global pollution. Stringent environmental policy will increase the production cost of pollution intensive goods and so resources will be reallocated to the production of the ‘clean’ goods. The reduction in the production of the ‘dirty’ goods along with the trade liberalization will result in a world excess demand for that good, which will create an incentive for foreign producers of the ‘dirty’ good to expand their production. The leakage effect is also present in the case where pollution is generated by consumption. Tighter environmental regulations in the home country will reduce the demand for ‘dirty’ goods and, consequently, their world price which in turn will increase the demand for these goods in the other countries. The overall effect of that leakage is ambiguous both theoretically and empirically (see among others Fullerton et al. (2011), Karp (2010), Levinson and Taylor (2008), Matoo et al. (2009) and Fischer and Fox (2009a, 2009b)).[27]

1.4 Environmental and trade policy reforms

The previous discussion reveals the complexity of the nexus between international trade and environmental policies. This complexity steams also from the transboundary nature of pollution: Countries have the incentive to free ride avoiding paying the cost of abatement. To overcome this market failure

[27] Because of these responses, environmental groups argue that a ‘race to the bottom’ (see, for instance, Sheldon (2006)) is the most likely (non-cooperative) outcome if countries compete in environmental standards.

multilateral agreements among countries of environmental and international trade polices are needed. Many studies have focused on the effects of environmental and trade policy reforms. Copeland (1994) examines the effects of environmental and trade policy reforms on a small open polluting economy establishing that there exist coordinating piecemeal reforms that deliver potential Pareto improvement. In particular, Copeland (1994) showed that reforms of either trade or environmental policy, in proportion to their deviation from their optimal level, are welfare improving. Having trade quotas as an alternative policy instrument, Copeland (1994) also concluded that policy coordination is also welfare increasing. He also showed that quotas and taxes are not equivalent and that policy reforms can be easier established in quota regimes than in tax ones (see also Neary (2006)).

Beqhin et al. (1997), extending Copeland (1994), allowed for polluting activities (both from the consumption and production side) and considered welfare-improving trade and environmental policy reforms. Decomposing the welfare and production effects of several policy instruments—tariffs, consumption and output taxes, and effluent taxes—they identified instances under which distortions of policy instruments in proportion to, and towards, their optimal level can increase welfare. Hatzipanayotou, et al. (2008), using a model of two small open economies with two goods and two-way cross-border pollution, studied the effects of changes in cross-border pollution on Nash emission taxes, emission levels and welfare. They showed that coordination of environmental policy increases welfare. The identification of (unilateral) Pareto improving policy reforms is also the focus of the Chapter 3. Departing from the above contributions, Chapter 3 shows that—within small open economies and with pollution taxes set optimally in a Nash fashion—there exist Pareto improving trade policy reforms.

Less attention has been paid to the issue of environmental policy reforms in large open economies. Turunen-Red and Woodland (2004) study the feasibility of Pareto-improving multilateral reforms of environmental policy. Using a model of many countries and many goods, they consider environmental and trade policy reforms showing that pollution-tax coordination, combined with income transfers, is welfare improving. They also argue that pollution-tax coordination is welfare improving if it is accompanied by a suitable tariff reform, in the absence of international transfers. Furthermore, by investigating the direct and indirect effects, they characterize a set of pollution-tax reforms that deliver strict Pareto improvements. More recently, Keen and Kotsogiannis (2012) focus on Pareto improving policy reforms in the sense of border tax adjustments (BTA). They consider a model with many countries and goods, with the available policy tools being carbon taxes and tariffs, and characterize—when the global economy is constrained inside the utility possibility frontier and only one country is able to change its environmental and trade policy—Pareto efficient carbon taxes and trade policies. They show that Pareto efficiency requires tariffs to account for the differences in carbon taxes between the 'constrained' and the 'unconstrained' countries, the aggregate terms of trade effect and the effects of tariffs on emissions and revenues. Furthermore, allowing for lump sum transfers, they argue that Pareto efficiency requires, when carbon and trade taxes are constrained in some countries, carbon taxes take the form of a BTA. Extending the analysis to consider cup-and-trade policies, they show that when that cap binds there is no BTA. When the cap does not bind, Pareto efficiency requires tariffs in the unconstrained country to embody BTAs.

In a similar context, Chapter 2 focuses on Pareto improving environmental policy harmonization reforms. Focusing on large open economies, Chapter 2 departs from the literature in several aspects. With pollution being either local or global and the only available fiscal policy instrument being pollution taxes, it characterizes the welfare consequences of pollution tax harmonization paying particular attention—in the achievement of Pareto improvements—to the allocation[28] of revenues *vis a vis* these reforms. It shows that starting from any non-Pareto efficient tax equilibrium a pollution tax harmonization reform, that moves the initial pollution taxes towards an appropriately weighted pollution tax vector, delivers potential Pareto improvements independently of the use of the collected tax revenues.

The issue of Pareto improving environmental policy reforms is also the focus of Chapter 5. This chapter discusses the case of environmental policies coordination among a subset of countries. With the only available fiscal policy instrument being the pollution taxes, it identifies the welfare effects of *partial* environmental policy coordination both on coordinating and non-coordinating countries' welfare. It argues that *partial* coordination of environmental policies have opposing effect on the welfare of the coordinating and non-coordinating countries.

1.5 Summary

This introductory chapter has provided a very selective introduction to the issues (partly addressed in the thesis), that I do not repeat here. It showed that while public and trade economists have made some progress on exploring the interactions between international trade and climate change, progress can only be realized (in welfare gains) if there is international cooperation. The thesis is (predominantly) devoted to this theme, by looking for reforms that are Pareto-improving. Though the thesis does not, by any means, provide the complete solution to the problem of cooperation, I believe that the analysis has

[28] Distributed to the consumers in a lump sum way or used to finance public abatement.

showed that the issue of coordination is an issue which deserves further attention.

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Chapter 2 The welfare consequences of pollution tax harmonization[1]

2.1 Introduction

The linkage of international trade and environment has been high on the policy agenda of international organizations, policymakers and the academic community. The reason for this stems from the recognition that increased trade might put downward pressure on environmental standards: Each country is unwilling to employ stricter environmental policies in the fear of worsening its competitive position in world markets, and instead they would prefer others to cut emissions thereby avoiding bearing the cost.[2] To circumvent this 'free-riding' problem multilateral coordination is needed—an issue that has been also advocated on the policy agenda of many international organizations (such as, to name a few, the OECD, GATT and IPCC).[3]

Environmental policy coordination has not been neglected in the literature. Predominantly, however, the research on this topic has focused on the case of *small* open economies, ignoring, in particular, all interesting interactions through the international goods market (see, among others, Copeland (1994),

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2 This is the so called 'pollution-haven' hypothesis. Though, it has to be noted, such hypothesis is not unanimously supported (see, for instance, Porter and van der Linde (1995)), there is increasing consensus that a significant portion of the increase in global temperature is a consequence of economic activity. For recent surveys on the issue see Chen and Woodland (2012) and Jones et al. (2012).

3 See, for instance, OECD (1974), GATT (The Agreement on Technical Barriers to Trade–the Standards Code–), IPCC (2007) and WTO(2004, 2009).

Hatzipanayotou et al. (2008), and Michael et al.(2011)).[4] More recently, attention has been paid to large open economies. Turunen-Red and Woodland (2004) discuss the feasibility of Pareto-improving multilateral reforms of environmental policy and trade policy.[5] This chapter contributes to this literature. Like Turunen-Red and Woodland (2004), this chapter looks at the welfare properties of reforms in a model of international trade with pollution being a by-product of production. Unlike them, however, the objective of this chapter is to discuss pollution tax harmonization paying particular attention—in the achievement of Pareto improvements—to the allocation of revenues *vis a vis* these reforms, as well as, the case of partial pollution tax harmonization.[6] As it will shown later on, a general characterization of Pareto-improving pollution tax reforms, though feasible, is not easily interpretable. For this—but also because such reforms have attracted increasing attention in the literature[7]—the present analysis will focus on a particular pollution tax harmonization reform: The one characterized by moving the initial pollution taxes towards an (appropriately weighted) pollution tax vector.

The analytics will show that such a reform—and starting from any non-Pareto efficient tax equilibrium—delivers potential Pareto improvements. And this is true independently of the use of the tax revenues collected (being distributed to the consumers in a lump sum way—as in Turunen-Red and Woodland

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4 See also Cramer and Gahvari (2004).

5 The link between environmental and trade policies—and the role of each policy for Pareto efficiency—are central in the analysis of Keen and Kotsogiannis (2012).

6 For a recent survey of the piecemeal reform literature see Santoro (2007).

7 This reform has been extensively used in Public Finance, and in the study of commodity-tax harmonization. See, for instance, Keen (1987) who has shown that a move of commodity taxes towards an appropriately weighted average would deliver a potential Pareto improvement. See also Delipalla (1997), Lahiri and Raimondos-Møller (1998), and Kotsogiannis, Myles and Lopez-Garcia (2005).

(2004)—or they are used to finance public abatement).

The rest of this chapter is organized as follows. Section 2.2 describes the model. Section 2.3 examines the welfare effects of pollution tax harmonization for both (and for completeness) small and large open economies, paying particular attention to the allocation of pollution tax revenues. Section 2.4 analyses the effects of partial harmonization (the harmonization, that is, of policy within a subset of countries). Finally, Section 2.5 summarizes and concludes.

2.2 Description of the model

The framework is familiar from Keen and Kotsogiannis (2012)[8] so the description of the model will be brief.

I consider a perfectly competitive general equilibrium of international trade in which there are J countries, indexed by the superscript j. In each country there is a private sector (with a representative consumer residing in each) which produces N tradable commodities. To focus on global welfare lump sum transfers between countries will be (implicitly) available.[9]

Production of these goods in each j country generates some pollutant, its level of which is denoted by the N-vector z^j.[10] Total emissions generated by the production in country j are, therefore, given by $i'z^j$, where i is the N-vector of 1s (and a prime denotes transposition). Global emissions, on which

8 Elements of this were also explored in the introductory chapter.
9 These transfers can be thought of as transfers of goods between countries evaluated at world prices.
10 Pollution is, therefore, modeled as a by-product of production (see, for instance, Copeland (1994), Turunen-Red and Woodland (2004) and Keen and Kotsogiannis (2012)).

damage in each country depends, are then given by

$$k = \sum_{j=1}^{J} i' z^j \ . \tag{2.1}$$

Pollution k thus confers disutility to consumers and does not affect the production capabilities of firms. Denoting by p the N-vector of international prices,[11] the representative consumer of country j has preferences represented by the expenditure function

$$e^j(u^j, p, k) = \min_{x^j} \{p' x^j : u^j(x^j, k) \geq \tilde{u}^j\} \ , \tag{2.2}$$

with, as an envelope property, e^j_p being the vector of compensated demands and e^j_k being the compensation required by the j country's consumer to accept a marginal increase in pollution k. Since pollution confers disutility $e^j_k > 0$.[12]

Pollution discharges in each country z^j are subject to sector-specific pollution taxes, given by the N-vector s^j. The private sector is perfectly competitive and characterized by the revenue function

$$r^j(p, s^j, v^j) = \max_{y,z} \{p' y^j - s^{j\prime} z^j : (y^j, z^j) \in \tau^j(v^j)\} \ , \tag{2.3}$$

where $\tau^j(v^j)$ is the j country's technology set, v^j is the vector of endowments, and y^j denotes the (net) output of tradeable goods. The revenue function in (2.3) has the standard properties: It is a convex

11 The analysis abstracts from tariffs and consumption taxes, not because they are unimportant but because they are, to some extent, well understood, see Turunen-Red and Woodland (2004).

12 The results presented here are expected to carry over—but with appropriate re-interpretation of variables—to the case in which pollution affects endowments, as in Kotsogiannis and Woodland (2012).

function, homogeneous of degree one in p and s^j and (assumed to be at least) twice continuously differentiable.[13] Hotelling's lemma implies that the vector of (net) supply functions for tradeable commodities is given by[14]

$$y^j = r_p^j\left(p, s^j\right)\ , \tag{2.4}$$

whereas the vector of emissions (associated with the production of the N tradeable goods) is given, as an envelope property, by

$$z^j = -r_s^j\left(p, s^j\right)\ , \tag{2.5}$$

implying, following from equation (2.1), that

$$k = -\sum_{j=1}^{J} i' r_s^j\ . \tag{2.6}$$

Notice, for later use that perturbation of (2.6) gives

$$dk = -\sum_{j=1}^{J} i'\left(r_{ss}^j ds^j + r_{sp}^j dp\right)\ . \tag{2.7}$$

Equation (2.7) is central to the analysis that follows: It simply says that the change in pollution depends on the sensitivity of the production sector in every country j to changes in pollution taxes and the prices of the tradeable commodities given by the matrices r_{ss}^j and r_{sp}^j, respectively. The analysis that follows imposes no restriction on these individual matrices.

13 Implicit in equation (2.3) is that the private production sector can abate environmental discharges by altering production patterns.

14 The endowment vectors, being fixed, are being suppressed from what follows.

The allocation of revenues will of course matter for the existence of Pareto-efficient pollution tax reforms. For the moment—and in line with Turunen-Red and Woodland (2004)—it will be taken that pollution tax revenues are returned to the consumer in a lump sum fashion (we postpone discussion to the case in which revenues are used to finance public abatement until Section 2.3.1).

The consumer's budget constraint in country j is given by

$$e^j(u^j, p, k) = r^j(p, s^j) + s^{j\prime} z^j \ , \tag{2.8}$$

and it simply says that expenditure, given by $e^j(u^j, p, k)$, is equal to GDP, given by $r^j(p, s^j)$, plus any pollution tax revenues collected, given by $s^{j\prime} z^j$.

Market clearing requires that

$$\sum_{j=1}^{J} \left\{ e^j_p(u^j, p, k) - r^j_p(p, s^j) \right\} = 0 \ . \tag{2.9}$$

Underlying equation (2.9) is a conventional normalization. The first traded commodity has been chosen as the numeraire, with its price being normalized to 1. Walras' Law then allows us to drop the market clearing condition for the numeraire good: There are thus $N - 1$ market clearing conditions.

Equations (2.8)-(2.9)—after making use (2.6)—characterize the equilibrium of this economy which consists of $N - 1 + J$ variables (u^j with $j = 1, ..., J$ and p).

Perturbing now equation (2.8)—making use of (2.7)—one obtains

$$e_u^j du^j = \left(-m^{j\prime} - s^{j\prime} r_{sp}^j + e_k^j \sum_{j=1}^{J} i' r_{sp}^j \right) dp + (e_k^j i - s^j)' r_{ss}^j ds^j + e_k^j \sum_{\substack{l=1 \\ l \neq j}}^{J} i' r_{ss}^l ds^l \ , \tag{2.10}$$

where $m^j \equiv e_p^j - r_p^j$ is the vector of imports of the non-numeraire goods for the home country. Equation (2.10) shows that each country's welfare depends on a number of effects.

- The first one, given by $-m^{j\prime} dp$, is the familiar terms of trade effect. If j country exports the non-numeraire goods, and so $m^j < 0$, then an increase in the price of these goods increases its welfare.
- The second effect, given by $\left(-s^{j\prime} r_{sp}^j + e_k^j \sum_{j=1}^{J} i' r_{sp}^j \right) dp,$ relates to the effect of prices on country j's welfare through changes in global pollution (the term $e_k^j \sum_{j=1}^{J} i' r_{sp}^j dp$) and through changes in pollution tax revenues and so the change in income returned to the consumer (the term $-s^{j\prime} r_{sp}^j dp$).
- The third effect, given by $(e_k^j i - s^j)' r_{ss}^j ds^j$, reflects the deviation of country j's pollution pricing from its own (local) marginal benefit derived from a change in own pollution taxes.
- Finally, the term $e_k^j \sum_{l=1}^{J} i' r_{ss}^l ds^l$ relates to the change in country j's utility when the other countries' pollution taxes change. It will be assumed that each country's income effects attach only to the numeraire good and so $e_{pu}^j = 0$.[15]

To obtain the global welfare consequences of changes in the fiscal instruments first perturb (2.9) to obtain

$$\Lambda dp = \sum_{j=1}^{J} \left[r_{ps}^j + \left(\sum_{\nu=1}^{J} e_{pk}^\nu \right) i' r_{ss}^j \right] ds^j \ , \tag{2.11}$$

with

$$\Lambda \equiv \sum_{j=1}^{J} \left[e_{pp}^j - r_{pp}^j - \left(\sum_{\nu=1}^{J} e_{pk}^\nu \right) i' r_{sp}^j \right] \ , \tag{2.12}$$

being an $(N-1) \times (N-1)$ matrix. The matrix Λ is the pollution-augmented world net substitution

15 Relaxation of this assumption is feasible at the cost of additional notation.

matrix for the non-numeraire goods and is, assumed to be, of full rank and so invertible. This guarantees that equation (2.9) can be implicitly solved for the world prices p, taking into account the (endogenous) determination of global pollution k and its impact on compensated demands in all countries.

Making use now of the perturbation of (2.10)—and applying (2.11)—one arrives at[16]

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{j=1}^{J} \left[\left(\sum_{\nu=1}^{J} e_k^{\nu} i \right) - s^j \right]' \delta^j, \tag{2.13}$$

where

$$\delta^j \equiv r_{sp}^j \Lambda^{-1} \left(\sum_{j=1}^{J} r_{ps}^j ds^j \right) + r_{sp}^j \Lambda^{-1} \left(\sum_{\nu=1}^{J} e_{pk}^{\nu} \right) \left(\sum_{j=1}^{J} i' r_{ss}^j ds^j \right) + r_{ss}^j ds^j,$$

It is now straightforward to verify[17] that, following from (2.13), Pareto efficiency dictates that

$$s^j = \sum_{\nu=1}^{J} e_k^{\nu} i > 0\ , \tag{2.14}$$

and so pollution taxes, from a global welfare perspective, are uniform *within* and *across* countries.[18] To emphasize:

Proposition 2.1 *Pareto efficiency dictates that pollution taxes satisfy* $s^j = \sum_{\nu=1}^{J} e_k^{\nu} i > 0$ *and so they are uniform within each country and across countries.*

Proposition 2.1 reconfirms the result in Keen and Kotsogiannis (2012):[19] Moving along the world's second best utility possibility frontier requires that each country set its pollution taxes in each sector so

16 Notice that underlying (2.13) is the existence of international transfers, the direction of which is of no importance here.

17 This will require taking the derivatives of (2.13) with respect to the pollution-tax vectors s^j and solving simultaneously the resulting first order conditions (assuming also that $\delta^j \neq 0$).

18 The inequality sign in (2.14) follows from the fact that $e_k^j > 0$.

19 We return to this in chapter 4.

to equate the value of income loss that this causes itself, given by s^j, to the sum of the damages $\sum_{\nu=1}^{J} e_k^{\nu} i$, that a marginal emission causes in all countries, both to itself and the other countries. Since the marginal impact of emission is the same whichever sector they originate in, each country sets the same pollution tax to all activities.

The analysis turns next to the search for Pareto improving pollution tax harmonizing reforms. For this to be meaningful it must be the case that the equilibrium is inconsistent with that of Proposition 2.1, so it is Pareto inefficient.

2.3 Pareto-improving pollution tax reforms

Close inspection of equation (2.10) reveals that the balance of the terms identified—and so the existence of Pareto improvements—cannot be easily established. The difficulty stems from the fact that changes in pollution taxes affect the international markets of the non-numeraire goods, and so the terms of trade in all countries. Absent such an effect, it is easy to verify that there exist proportional changes in pollution taxes (that are not necessarily harmonizing in the sense to made precise shortly below) that increase global welfare. To see this take (2.10) to obtain, after setting $dp = 0$

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{j=1}^{J} \left[\left(\sum_{\nu=1}^{J} e_k^{\nu} \right) i - s^j \right]' r_{ss}^j ds^j \ . \tag{2.15}$$

Equation (2.15) simply says that global welfare depends on the deviation of pollution taxes from their marginal benefits. In this case, it is not difficult to find instances under which an appropriate change of pollution taxes deliver a potential Pareto improvement: This will be, for instance, the case if pollution taxes in both countries were to move towards their Pareto efficient level (established in Proposition 1). To see this suppose that pollution taxes change according to

$$ds^j = \left[\left(\sum_{\nu=1}^{J} e_k^\nu \right) i - s^j \right] d\lambda^j \ , \tag{2.16}$$

with $d\lambda^j > 0$ (and scalars). In this case we have that

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{j=1}^{J} \left\{ \left[\left(\sum_{\nu=1}^{J} e_k^\nu \right) i - s^j \right]' r_{ss}^j \left[\left(\sum_{\nu=1}^{J} e_k^\nu \right) i - s^j \right] d\lambda^j \right\} \geq 0 \ , \tag{2.17}$$

with the inequality sign following from the fact that r_{ss}^j is a positive semidefinite matrix.[20] To emphasize:

Proposition 2.2 *Starting from any arbitrary pollution tax distorted equilibrium with* $\sum_{\nu=1}^{J} e_k^\nu i \neq s^j$*, equiproportional changes of pollution taxes, in the sense of* $ds^j = \left[\sum_{\nu=1}^{J} e_k^\nu i - s^j \right] d\lambda^j$ *and with* $d\lambda^j > 0$*, deliver a potential Pareto improvement.*

Proposition 2.2 extends the small open economy with local pollution result in Copeland (1994) and Neary (2006) to a small open economy with global pollution.

Though the result of Proposition 2.2 is, arguably, insightful it is rather restrictive as it ignores all interesting interactions through the international goods market. The analysis turns to this next.

To simplify matters it will be also assumed that, in each country, one unit of output generates α units of pollutants. This assumption allows us to express the amount of generated pollution as a function

[20] This is reminiscent of Dixit (1985) and, in a similar context, Baumol and Oates (1988), that equiproportionate reductions in distortions (pollution here) can be welfare improving.

of the produced output and so $y^j = az^j$ and, since $r_p^j = y^j$ and $r_s^j = -z^j$, thus

$$r_p^j = -ar_s^j \ , \tag{2.18}$$

where $a > 0$. This implies that

$$r_{ps}^j = -ar_{ss}^j \ . \tag{2.19}$$

I now turn to pollution tax harmonization and to a reform that generates a potential Pareto improvement. Consider pollution tax reforms that imply a non-uniform proportional convergence of domestic pollution tax structures towards a target vector H given by[21]

$$ds^j = \beta \left(H - s^j \right) \ , \tag{2.20}$$

where β is a small positive scalar and H–the common target for the pollution taxes–is an $N \times 1$ vector given by

$$H = \left[\sum_{j=1}^{J} r_{ss}^j \right]^{-1} \left[\sum_{j=1}^{J} r_{ss}^j s^j \right] \ . \tag{2.21}$$

Making use of (2.21) into (2.20) it is the case that

$$ds^j = \left[\sum_{j=1}^{J} r_{ss}^j \right]^{-1} \beta \left[\sum_{\substack{l=1 \\ l \neq j}}^{J} r_{ss}^l \left(s^l - s^j \right) \right] \ , \tag{2.22}$$

and so

$$\sum_{j=1}^{J} r_{ss}^j ds^j = 0 \ , \tag{2.23}$$

21 As noted earlier (see footnote 7) this reform is not uncommon in the Public Finance literature.

which implies—following from (2.11) and using (2.19)—that

$$dp = 0 \ , \tag{2.24}$$

and so production prices (and, in the absence of consumption taxes, consumer prices) remain unchanged as a consequence of pollution tax harmonization. Global welfare, in this case, is given—following from (2.10)—by

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{j=1}^{J} \left[\left(\sum_{\nu=1}^{J} e_k^\nu \right) i - s^j \right]' r_{ss}^j ds^j \ . \tag{2.25}$$

Making now use of (2.23), (2.25) reduces to

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{\substack{j=1 \\ j \neq h}}^{J} \left(s^h - s^j \right)' r_{ss}^j ds^j \ , \tag{2.26}$$

which upon making use of (2.22) implies that[22]

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{j=1}^{J} \left\{ \sum_{\substack{\mu=1 \\ \mu > j}}^{J} \left[\left(s^j - s^\mu \right)' r_{ss}^\mu \left(\sum_{j=1}^{J} r_{ss}^j \right)^{-1} \beta r_{ss}^j \left(s^j - s^\mu \right) \right] \right\} \geq 0 \ , \tag{2.27}$$

with the inequality following from the fact that r_{ss}^j is a positive semidefinite matrix. To summarize:

Proposition 2.3 *Starting from any arbitrary pollution tax distorted equilibrium* $s^\mu \neq s^j \ \forall \ \mu, j \in [1, J]$, *and assuming that one unit of output generates* α *units of pollutant, the pollution tax harmonizing reform (2.20)-(2.21) delivers a potential Pareto improvement.*

There is some simple intuition behind this proposition. The pollution tax-harmonizing reform induces producer prices (and consumer prices) to remain constant at equilibrium level p. With constant

[22] Details of this are relegated to Appendix A.

producer prices the value of imports remains unaffected. The pollution tax harmonizing reforms then induces changes in the production of the tradeable goods—through the change in the pollution taxes—and so in the intensity of pollution in all countries and, as a consequence, in the revenues (and so income) that are being distributed to the consumer.

The question that naturally arises then is the extent to which the welfare consequences of pollution tax harmonization carries over to the case in which pollution tax revenues are used to provide public abatement. I turn to this next.

2.3.1 Public abatement and pollution tax harmonization

Suppose now that pollution tax revenues finance public abatement that benefit, through a reduction in the impact of global pollution, consumers. To obtain a better understanding of the forces at work, the analysis will start by treating pollution as a local public bad, turning next to the treatment of transboundary pollution.

2.3.1.1 Local pollution

The economy is as before with the only difference being that pollution now in each country is given by

$$k^j = -i' r_s^j + s^{j\prime} r_s^j \,, \tag{2.28}$$

where[23]

$$g^j = -s^{j\prime} r_s^j \left(p, s^j\right) \ , \tag{2.29}$$

is public abatement. To focus on the implications of public abatement for the existence of pollution tax harmonizing reforms, it is assumed that public production consists of purchases of the numeraire good. Notice, for later use, that perturbation of (2.28), and making use of (2.29), gives

$$dk^j = -\left(i - s^j\right)' r_{sp}^j dp - \left(i - s^j\right)' r_{ss}^j ds^j + r_s^{j\prime} ds^j \ , \tag{2.30}$$

and so changes in local pollution depends on revenues collected (and so the size of public abatement expenditure) and the pollution intensity of the production sector in the corresponding country.

With country j's budget constraint being

$$e^j(p, u^j, k^j) = r^j(p, s^j) \ , \tag{2.31}$$

the equilibrium (assuming again it exists) is now defined by (2.9), (2.28), (2.29) and (2.31). Perturbing the equilibrium one arrives at

$$e_u^j du^j = [-m^{j\prime} + e_k^j (i - s^j)' r_{sp}^j] dp + e_k^j (i - s^j)' r_{ss}^j ds^j - \left(e_k^j - 1\right) r_s^{j\prime} ds^j \ . \tag{2.32}$$

Equation (2.32) show that country j's welfare depends on effects induced by changes in the terms-of-trade and the policy instruments. These effects are similar to the ones discussed previously, with the added

23 An alternative specification would be to assume that the benefit from public abatement is a function $f(g^j)$, with $f'(g^j) > 0 > f''(g^j)$ (a prime denotes the derivative of the function).

element here being that k is now net pollution (being affected by the existence of public abatement). The implication of this is (as a consequence of pollution tax harmonization, and a requirement for a welfare improvement) the differences in the marginal benefit from a reduction in pollution matters. To see this take aggregate welfare

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{j=1}^{J} e_k^j \left(i - s^j\right)' r_{sp}^j dp + \sum_{j=1}^{J} e_k^j \left(i - s^j\right)' r_{ss}^j ds^j - \sum_{j=1}^{J} e_k^j r_s'^j ds^j + \sum_{j=1}^{J} r_s'^j ds^j \ , \tag{2.33}$$

with dp (after making use of (2.19) and (2.23) which imply $\sum_{j=1}^{J} r_{ps}^j ds^j = 0$) being given by

$$\Lambda dp = \sum_{j=1}^{J} e_{pk}^j \left[\left(i - s^j\right)' r_{ss}^j - r_s^{j\prime}\right] ds^j \ , \tag{2.34}$$

where

$$\Lambda = \sum_{j=1}^{J} \left(e_{pp}^j - r_{pp}^j - e_{pk}^j \left(i - s^j\right)' r_{sp}^j\right) \ , \tag{2.35}$$

is a $(N-1) \times (N-1)$ matrix. Closer inspection of equations (2.33) and (2.34) reveals that the pollution tax harmonization reforms (2.20), (2.21) point to some instances where they are potentially welfare increasing. To see this suppose, for instance, that pollution does not affect the compensated demands of any good in every country j other than the numeraire, that is $e_{pk}^j = 0$, then $dp = 0$ and so the aggregate welfare given by

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{j=1}^{J} \left[e_k^j \left[(i - s^j)' r_{ss}^j - r_s^{j\prime}\right] + r_s^{j\prime}\right] ds^j \ . \tag{2.36}$$

Clearly, if the compensation required by the consumer to accept a marginal increase in pollution is the same across countries, and equal to 1, (in the sense that $e_k^j = 1$), then

$$\begin{aligned}\sum_{j=1}^{J} e_u^j du^j &= \sum_{j=1}^{J} (i - s^j)' r_{ss}^j ds^j , \\ &= \sum_{\substack{j=1 \\ j \neq h}}^{J} \left(s^h - s^j\right)' r_{ss}^j ds^j \ , \\ &= \sum_{j=1}^{J} \left\{ \sum_{\substack{\mu=1 \\ \mu > j}}^{J} \left[\left(s^j - s^\mu\right)' r_{ss}^\mu \left(\sum_{j=1}^{J} r_{ss}^j \right)^{-1} \beta r_{ss}^j \left(s^j - s^\mu\right) \right] \right\} \geq 0 \ , \end{aligned} \tag{2.37}$$

where the second equality follows from (2.23), and the third from (2.20) and (2.21) and the inequality from the fact that r_{ss}^j is positive semidefinite matrix for every $j \in (0, J)$.

This will also be the case if the consumer's marginal willingness to pay for a reduction in pollution across countries is the same, in the sense that $e_k^j = \overline{e}$, and global pollution tax revenues are conditional revenue neutral in the sense that[24]

$$\sum_{j=1}^{J} \left[\left(s^{j\prime} r_{ss}^j + r_s^{\prime j} \right) ds^j + s^{j\prime} r_{sp}^j dp \right] = 0 \ . \tag{2.38}$$

It is easy to verify that in this case (2.36) reduces to

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{\substack{j=1 \\ j \neq h}}^{J} \left(s^h - s^j\right)' r_{ss}^j ds^j \ , \tag{2.39}$$

24 The conditionality on the revenue neutrality is driven by the pollution tax harmonization reform. The pollution tax harmonization induces the first and second order effects on the changes of global revenues to be equal, see equation (2.38).

and so—upon making use of ds^j from (2.22)—to

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{j=1}^{J} \left\{ \sum_{\substack{\mu=1 \\ \mu>j}}^{J} \left[\left(s^j - s^\mu\right)' r_{ss}^\mu \left(\sum_{j=1}^{J} r_{ss}^j \right)^{-1} \beta r_{ss}^j \left(s^j - s^\mu\right) \right] \right\} \geq 0 \, . \tag{2.40}$$

It can be straightforwardly shown that even with $e_{pk}^j \neq 0$ there exist welfare-enhancing pollution tax harmonization reforms. To see this suppose that $e_k^j = \overline{e}$, $\forall \, j$, and so the consumer's marginal willingness to pay for a reduction in pollution is the same across countries,[25] but also tax revenues are conditional neutral (implying that prices are constant at their pre reform level, $dp = 0$). In this case equation (2.33) reduces to

$$\sum_{j=1}^{J} e_u^j du^j = - \sum_{j=1}^{J} s^{j\prime} r_{ss}^j ds^j \, , \tag{2.41}$$

and so—upon making use of pollution tax harmonization reforms—to

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{j=1}^{J} \left\{ \sum_{\substack{\mu=1 \\ \mu>j}}^{J} \left[\left(s^j - s^\mu\right)' r_{ss}^\mu \left(\sum_{j=1}^{J} r_{ss}^j \right)^{-1} \beta r_{ss}^j \left(s^j - s^\mu\right) \right] \right\} \geq 0 \, . \tag{2.42}$$

To emphasize the preceding discussion:

Proposition 2.4 *Assuming that pollution is a local public bad, then the pollution tax harmonizing reform (2.20) and (2.21), starting from an arbitrary pollution tax distorted equilibrium with $s^\mu \neq s^j \; \forall \; \mu, j \in (1, J)$, delivers a potential Pareto improvement, if either of the following holds:*

i) pollution does not affect compensated demands of any good other than the numeraire, $e_{pk}^j = 0$, and

(a) the consumer's marginal willingness to pay for a reduction of pollution is the same across countries and equal to 1, $e_k^j = 1$, or

(b) the consumer's marginal willingness to pay for a reduction of pollution is the same across countries and equal to a constant $\overline{e}$, in the sense $e_k^j = \overline{e}$, and the pollution tax-harmonizing reforms are conditionally-revenue neutral,

25 Notice that if $e_k^j = \overline{e}$ also e_{pk}^j is uniform across countries.

ii) pollution affects the compensated demands of all tradable goods, $e^j_{pk} \neq 0$, the consumer's marginal willingness to pay for a reduction of pollution is the same across countries, $e^j_k = \overline{e}$, and the pollution tax-harmonizing reforms are conditionally-revenue neutral.

Proposition 2.4 shows that pollution tax harmonization, when pollution is local, can be welfare improving even in the presence of public abatement. The question that now arises is whether Proposition 2.4 holds in the presence of transboundary pollution. I turn to this next.

2.3.1.2 Transboundary pollution

Suppose now that (net) pollution is given by

$$k = \sum_{j=1}^{J} \left(i' z^j - g^j \right) \ , \tag{2.43}$$

and so is global.

Equilibrium is now characterized by (2.9), (2.29), (2.31), and (2.43). Perturbing these equations it is straightforward to verify that

$$e^j_u du^j = \left(-m^j + e^j_k \sum_{j=1}^{J} \left(i - s^j \right)' r^j_{sp} \right) dp + e^j_k \sum_{j=1}^{J} \left(i - s^j \right)' r^j_{ss} ds^j - e^j_k \sum_{j=1}^{J} r'^j_s ds + r'^j_s ds^j \ , \tag{2.44}$$

with dp (after making use of (2.19) and (2.23) which imply that $\sum_{j=1}^{J} r^j_{ps} ds^j = 0$) being given by

$$\Lambda dp = - \left(\sum_{j=1}^{J} e^j_{pk} \right) \left[\sum_{j=1}^{J} \left(s^{j\prime} r^j_{ss} + r'^j_s \right) ds^j \right] \ , \tag{2.45}$$

with

$$\Lambda = \sum_{j=1}^{J} \left\{ e^j_{pp} - r^j_{pp} + e^j_{pk} \left[\sum_{j=1}^{J} \left(i - s^j \right)' r^j_{sp} \right] \right\} , \tag{2.46}$$

being a $(N-1) \times (N-1)$ matrix, assumed to be of full rank and so invertible.

Assuming that pollution does not affect the compensated demands of any good other than the numeraire, that is $e^j_{pk} = 0$, implies that $dp = 0$ and so each country's welfare is given by

$$e^j_u du^j = -\left(e^j_k \right) \left[\sum_{j=1}^{J} \left(s^{j\prime} r^j_{ss} + r^{j\prime}_s \right) ds^j \right] + r'^j_s ds^j . \tag{2.47}$$

It is straightforward to verify that if the revenues are conditional revenue neutral, in the sense that $\sum_{j=1}^{J} dg^j = 0$, then

$$\sum_{j=1}^{J} e^j_u du^j = \sum_{\substack{j=1 \\ j \neq h}}^{J} \left(s^h - s^j \right)' r^j_{ss} ds^j ,$$

which upon making use of (2.22) becomes

$$\sum_{j=1}^{J} e^j_u du^j = \sum_{j=1}^{J} \left\{ \sum_{\substack{\mu=1 \\ \mu > j}}^{J} \left[\left(s^j - s^\mu \right)' r^\mu_{ss} \left(\sum_{j=1}^{J} r^j_{ss} \right)^{-1} \beta r^j_{ss} \left(s^j - s^\mu \right) \right] \right\} \geq 0 . \tag{2.48}$$

This will also be the case if changes in pollution affect the compensated demands of all tradable goods $e^j_{pk} \neq 0$ and global pollution tax revenues are conditionally-revenue neutral in the sense that

$$\sum_{j=1}^{J} \left(s^{j\prime} r^j_{ss} + r'^j_s \right) ds^j = 0 . \tag{2.49}$$

This implies that $dp = 0$, and so aggregate welfare reduces to

$$\sum_{j=1}^{J} e_u^j du^j = -\sum_{j=1}^{J} s^{j\prime} r_{ss}^j ds^j \ .$$

Making use of the pollution tax harmonization reforms (2.20) and (2.21) it is the case that

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{j=1}^{J} \left\{ \sum_{\substack{\mu=1 \\ \mu>j}}^{J} \left[\left(s^j - s^\mu\right)' r_{ss}^\mu \left(\sum_{j=1}^{J} r_{ss}^j \right)^{-1} \beta r_{ss}^j \left(s^j - s^\mu\right) \right] \right\} \geq 0 \ . \tag{2.50}$$

I thus arrive at:

Proposition 2.5 *Assuming that pollution is a global public bad, then the pollution tax harmonizing reform in (2.20) and (2.21), starting from an arbitrary pollution tax distorted equilibrium with* $s^\mu \neq s^j \ \forall \ \mu, j \in (1, J)$*, delivers a potential Pareto improvement, if either of the following holds:*

i) pollution does not affect the compensated demands of any good other than the numeraire, $e_{pk}^j = 0$*, and the pollution tax-harmonizing reforms are conditionally-revenue neutral,*

ii) pollution affect the compensated demands of all tradable goods, $e_{pk}^j \neq 0$*, and the pollution tax-harmonizing reforms are conditionally-revenue neutral.*

Proposition 2.5 shows that environmental policy harmonization can be welfare improving in the presence of public abatement and transboundary pollution. There is some straightforward intuition behind this result. Pollution-tax harmonization implies that international prices remain constant, at their pre-reform level, and so do consumer demands and emission discharges—in the sense of $r_{sp}^i = 0$. Environmental policy, however, induces firms to adjust their production pattern by altering the pollution intensity of the tradeable goods conferring a welfare benefit to consumers.

The question that naturally arises next is whether the welfare consequences of pollution tax harmonization carries over to the case of partial pollution tax harmonization, in the sense that a subset of countries harmonize their environmental polices while another (for simplicity we assume one country) do not participate. I turn to this next.

2.4 Regional Harmonization

The analysis now turns to the case of partial pollution tax harmonization. Suppose that the economy is as the one described in Section 2 but now only $J-1$ of them harmonize their policies while one—indexed by θ—does not. For country θ pollution taxes are kept fixed at their equilibrium level.

The equilibrium is now characterized by (2.6), (2.8) and (2.9). Notice, for later use, that pertubation of (2.6)—given that country's θ pollution taxes are held fixed—gives

$$dk = -\sum_{\substack{j=1 \\ j\neq\theta}}^{J} i' r_{ss}^{j} ds^{j} - \sum_{j=1}^{J} i' r_{sp}^{j} dp \ . \tag{2.51}$$

Perturbing now the equilibrium one arrives at

$$e_u^j du^j = \left(-m^j - s^{j\prime} r_{sp}^j + e_k^j \sum_{j=1}^{J} i' r_{sp}^j \right) dp - s^{j\prime} r_{ss}^j ds^j + e_k^j \sum_{\substack{j=1 \\ j\neq\theta}}^{J} i' r_{ss}^j ds^j \ , \tag{2.52}$$

and

$$e_u^\theta du^\theta = \left(-m^\theta - s^{\theta\prime} r_{sp}^\theta + e_k^\theta \sum_{j=1}^{J} i' r_{sp}^j \right) dp + e_k^\theta \sum_{\substack{j=1 \\ j\neq\theta}}^{J} i' r_{ss}^j ds^j \ , \tag{2.53}$$

Notice here, and in contrast to the previous cases, that the country's θ welfare depends only on the environmental policies of the participating countries, since this country keeps its pollution taxes fixed at their equilibrium level.

Perturbing the international prices gives

$$dp = \Lambda^{-1} \left[\sum_{\substack{j=1 \\ j \neq \theta}}^{J} r_{ps}^{j} ds^{j} + \left(\sum_{j=1}^{J} e_{pk}^{j} \right) \left(\sum_{\substack{j=1 \\ j \neq \theta}}^{J} i' r_{ss}^{j} ds^{j} \right) \right] , \tag{2.54}$$

with

$$\Lambda \equiv \sum_{j=1}^{J} e_{pp}^{j} - \sum_{j=1}^{J} r_{pp}^{j} - \left(\sum_{j=1}^{J} e_{pk}^{j} \right) \left(\sum_{j=1}^{J} i' r_{sp}^{j} \right) , \tag{2.55}$$

being a $(N-1) \times (N-1)$ matrix, assumed to have full rank and so be invertible.

Consider now the harmonization reform, consistent with the reform described by equations (2.20) and (2.21), for the $J-1$ countries

$$ds^{j} = \beta \left(H - s^{j} \right) \quad \forall j \in [1, J] : j \neq \theta , \tag{2.56}$$

where β is a small positive scalar and H—the common target for the pollution taxes of the $J-1$ countries—is an $N \times 1$ vector and given by

$$H = \left[\sum_{\substack{j=1 \\ j \neq \theta}}^{J} r_{ss}^{j} \right]^{-1} \left[\sum_{\substack{j=1 \\ j \neq \theta}}^{J} r_{ss}^{j} s^{j} \right] . \tag{2.57}$$

The implication of this is that

$$ds^{j} = \left[\sum_{\substack{j=1 \\ j \neq \theta}}^{J} r_{ss}^{j} \right]^{-1} \beta \left[\sum_{\substack{l=1 \\ l \neq j, \theta}}^{J} r_{ss}^{l} \left(s^{l} - s^{j} \right) \right] , \tag{2.58}$$

and so

$$\sum_{\substack{j=1\\ j\neq\theta}}^{J} r_{ss}^{j} ds^{j} = 0 \;, \tag{2.59}$$

which implies that—given (2.54) and using (2.19)—the international goods prices remain unchanged as a consequence of the pollution tax harmonization, $dp = 0$. It is so the case that

$$\sum_{\substack{j=1\\ j\neq\theta}}^{J} e_{u}^{j} du^{j} = \sum_{\substack{j=1\\ j\neq h,\theta}}^{J} \left(s^{h} - s^{j}\right)' r_{ss}^{j} ds^{j} \;, \tag{2.60}$$

which, upon making use of (2.58), becomes

$$\sum_{\substack{j=1\\ j\neq\theta}}^{J} e_{u}^{j} du^{j} = \sum_{\substack{j=1\\ j\neq\theta}}^{J} \left\{ \sum_{\substack{\mu=1\\ \mu>j\\ j\neq\theta}}^{J} \left[\left(s^{j} - s^{\mu}\right)' r_{ss}^{\mu} \left(\sum_{\substack{j=1\\ j\neq\theta}}^{J} r_{ss}^{j} \right)^{-1} \beta r_{ss}^{j} \left(s^{j} - s^{\mu}\right) \right] \right\} \geq 0 \;. \tag{2.61}$$

I so arrive at:

Proposition 2.6 *Starting from any arbitrary pollution tax distorted equilibrium* $s^{\mu} \neq s^{j}\; \forall\, \mu, j \in [1, J-1]$*, regional pollution tax harmonization (2.56)-(2.57) delivers a potential Pareto improvement.*

The fact that regional pollution tax harmonization delivers potential Pareto improvement is intuitive: With international prices and global emissions level fixed at their equilibrium level, as a consequence of pollution tax harmonization, environmental policy reforms induces firms, of the participating countries, to adjust the pollution intensity of their production. Consequently the consumers welfare, of the participating countries, is affected by the changes on the collected revenues. Additionally, proposition 2.6 implies that the welfare of the non-participating county's consumer is not affected by the pollution tax harmonization reform due to its effects on international prices and global emissions level.

2.5 Concluding remarks

This chapter has investigated the existence of, starting from any non-Pareto efficient pollution tax equilibrium, potential Pareto improving pollution tax harmonizing reforms. It has shown that, in large open economies pollution tax harmonization, of a particular type, does deliver potential Pareto improvements. And this is true independently of the use of the tax revenues collected (either being distributed to the consumers in a lump sum way or being used to finance public abatement). Additionally the analysis shows that these results carry over to the case of partial pollution tax harmonization.

The limitation of the present analysis suggests avenues for future research. For the evaluation of the reforms the welfare criterion has been potential Pareto improvements. It will be desirable (and more challenging too) to extend the framework to the search of reforms (in the lines of Turunen-Red and Woodland (2004)) that deliver strict Pareto improvements. The role (if there is any) of non-tradeable goods has also been ignored. Given the importance of such goods extending the present framework is desirable.

Despite these limitations, however, I hope to have shown that the results obtained are instructive and could serve as stepping stones to future explorations of reforms in more general settings.

Appendix A

Proof of equation (2.27):

Equation (2.25) can be written as

$$\sum_{j=1}^{J} e_u^j du^j = \left(\sum_{\nu=1}^{J} e_k^{\nu} i' \right) \sum_{j=1}^{J} r_{ss}^j ds^j - \sum_{j=1}^{J} s^{j\prime} r_{ss}^j ds^j \ , \tag{A.1}$$

which upon making use of (2.23) reduces to

$$\sum_{j=1}^{J} e_u^j du^j = -s^{k\prime} r_{ss}^k ds^k - \sum_{j \neq k}^{J} s^{j\prime} r_{ss}^j ds^j \ . \tag{A.2}$$

Making use of the fact that—following from (2.23)—$r_{ss}^k ds^k = -\sum_{j \neq k}^{J} r_{ss}^j ds^j$ aggregate welfare is given by

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{j \neq k}^{J} \left(s^k - s^j \right)' r_{ss}^j ds^j \ . \tag{A.3}$$

Rewriting (A.3), after setting $k = 1$, one obtains

$$\sum_{j=1}^{J} e_u^j du^j = \left(s^1 - s^2 \right)' r_{ss}^2 ds^2 + \left(s^1 - s^3 \right)' r_{ss}^3 ds^3 + \left(s^1 - s^J \right)' r_{ss}^4 ds^4 + ... + \left(s^1 - s^J \right)' r_{ss}^J ds^J \ , \tag{A.4}$$

which upon substituting in ds^j, from equation (2.22), it becomes

$$\sum_{j=1}^{J} e_u^j du^j = \left(s^1 - s^2 \right)' r_{ss}^2 \left[\sum_{j=1}^{J} r_{ss}^j \right]^{-1} \beta \left[\sum_{l \neq 2}^{J} r_{ss}^l \left(s^l - s^2 \right) \right]$$
$$+ \left(s^1 - s^3 \right)' r_{ss}^3 \left[\sum_{j=1}^{J} r_{ss}^j \right]^{-1} \beta \left[\sum_{l \neq 3}^{J} r_{ss}^l \left(s^l - s^3 \right) \right] + ... + \left(s^1 - s^J \right)' r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j \right]^{-1} \beta \left[\sum_{l \neq j}^{J} r_{ss}^l \left(s^l - s^J \right) \right] \ . \tag{A.5}$$

Decomposing now the appropriate rhs summations one arrives at

$$\sum_{j=1}^{J} e_u^j du^j = \left(s^1 - s^2\right)' r_{ss}^2 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^1 \left(s^1 - s^2\right) + \left(s^1 - s^2\right)' r_{ss}^2 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^3 \left(s^3 - s^2\right)$$
$$+ ... + \left(s^1 - s^2\right)' r_{ss}^2 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^J \left(s^J - s^2\right)$$
$$+ \left(s^1 - s^3\right)' r_{ss}^3 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^1 \left(s^1 - s^3\right) + \left(s^1 - s^3\right)' r_{ss}^3 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^2 \left(s^2 - s^3\right)$$
$$+ ... + \left(s^1 - s^3\right)' r_{ss}^3 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^J \left(s^J - s^3\right)$$
$$+ ... + \left(s^1 - s^J\right)' r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^1 \left(s^1 - s^J\right) + \left(s^1 - s^J\right)' r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^2 \left(s^2 - s^J\right)$$
$$+ \left(s^1 - s^J\right)' r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^3 \left(s^3 - s^J\right) + .. + \left(s^1 - s^J\right)' r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^{J-1} \left(s^{J-1} - s^J\right) \ . \tag{A.6}$$

(A.6) can be written as

$$\sum_{j=1}^{J} e_u^j du^j = \left(s^1 - s^2\right)' r_{ss}^2 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^1 \left(s^1 - s^2\right) + \left(s^1 - s^3\right)' r_{ss}^3 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^1 \left(s^1 - s^3\right)$$

$$+ ... + \left(s^1 - s^J\right)' r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^1 \left(s^1 - s^J\right)$$

$$- s^{1\prime} r_{ss}^2 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^3 \left(s^2 - s^3\right) + s^{2\prime} r_{ss}^2 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^3 \left(s^2 - s^3\right)$$

$$+ ... - s^{1\prime} r_{ss}^2 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^J \left(s^2 - s^J\right) + s^{2\prime} r_{ss}^2 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^J \left(s^2 - s^J\right)$$

$$+ s^{1\prime} r_{ss}^3 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^2 \left(s^2 - s^3\right) - s^{3\prime} r_{ss}^3 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^2 \left(s^2 - s^3\right)$$

$$+ ... - s^{1\prime} r_{ss}^3 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^J \left(s^3 - s^J\right) + s^{3\prime} r_{ss}^3 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^J \left(s^3 - s^J\right)$$

$$+ ... + s^{1\prime} r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^2 \left(s^2 - s^J\right) - s^{J\prime} r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^2 \left(s^2 - s^J\right) +$$

$$s^{1\prime} r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^3 \left(s^3 - s^J\right) - s^{J\prime} r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^3 \left(s^3 - s^J\right)$$

$$+ .. + s^{1\prime} r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^{J-1} \left(s^{J-1} - s^J\right) - s^{J\prime} r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^{J-1} \left(s^{J-1} - s^J\right) \ . \tag{A.7}$$

Since r_{ss}^j is symmetric, which implies that $r_{ss}^i \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^l = r_{ss}^l \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^i$, equation (A.7) becomes

$$\sum_{j=1}^{J} e_u^j du^j = \left(s^1 - s^2\right)' r_{ss}^2 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^1 \left(s^1 - s^2\right) + \left(s^1 - s^3\right)' r_{ss}^3 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^1 \left(s^1 - s^3\right)$$
$$+ ... + \left(s^1 - s^J\right)' r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^1 \left(s^1 - s^J\right)$$
$$+ \left(s^2 - s^3\right)' r_{ss}^3 \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^2 \left(s^2 - s^3\right) + ... + \left(s^2 - s^J\right)' r_{ss}^j \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^2 \left(s^2 - s^J\right)$$
$$+ ... + \left(s^{J-1} - s^J\right)' r_{ss}^J \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^{J-1} \left(s^{J-1} - s^J\right) \ . \tag{A.8}$$

Tidying up the rhs of equation (A.8) one obtains

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{\mu=2}^{J} \left\{ \left(s^1 - s^\mu\right)' r_{ss}^\mu \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^1 \left(s^1 - s^\mu\right) \right\}$$
$$+ \sum_{\mu=3}^{J} \left\{ \left(s^2 - s^\mu\right)' r_{ss}^\mu \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^2 \left(s^2 - s^\mu\right) \right\}$$
$$+ ... + \sum_{\mu=J-1}^{J} \left\{ \left(s^{J-2} - s^\mu\right)' r_{ss}^\mu \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^{J-2} \left(s^{J-2} - s^\mu\right) \right\}$$
$$+ \left(s^{J-1} - s^J\right)' r_{ss}^{J-1} \left[\sum_{j=1}^{J} r_{ss}^j\right]^{-1} \beta r_{ss}^J \left(s^{J-1} - s^J\right) \ . \tag{A.9}$$

Close inspection of equation (A.9) reveals that it can be written as

$$\sum_{j=1}^{J} e_u^j du^j = \sum_{j=1}^{J} \left\{ \sum_{\substack{\mu=1 \\ \mu>j}}^{J} \left[\left(s^j - s^\mu\right)' r_{ss}^\mu \left(\sum_{j=1}^{J} r_{ss}^j\right)^{-1} \beta r_{ss}^j \left(s^j - s^\mu\right) \right] \right\} , \tag{A.9}$$

confirming (2.27).

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Chapter 3 Tariff reforms in the presence of pollution

3.1 Introduction

The Intergovernmental Panel on Climate Change (2007) predicts that under 'business as usual' the global mean temperature over the next century will increase by 2.8^{o}C, with a 3% chance of the temperature rising to 6^{o}C or more. The potential (both physical and economic) consequences of such considerable increase in the level of temperature are likely to be catastrophic (Stern et al. (2006) and Jones et al. (2012)).[1] To reduce the adverse impact of dangerous levels of atmospheric greenhouse gases concentration, it would be required, collectively, to slow and then cut global emissions by a substantial 50-80 percent in developed countries.[2]

In response to this challenge, a number of countries are considering, mainly as part of their obligations under the current treaties, domestic action to address climate change. One of the major obstacles, however, in those countries towards taking such action, is the concern that it may put their domestic industries at a disadvantage relative to produces in countries that do not take similar actions. At the heart of this issue there is a classic-free rider problem. The reduction of greenhouse gases is a global public good and so each country would prefer the others to cut emissions thereby avoiding bearing the cost.

The issue of unilateral governments actions has not been neglected in the literature. One policy that

1 Special thanks to Christos Kotsogiannis for introducing me to the issue of border tax adjustments, and for sharing with me part of his unpublished research on the topic.

2 For recent—and insightful—surveys on the issue see Chen and Woodland (2012) and Jones et al. (2012).

has been repeatedly proposed to deal with this challenge is border-tax-adjustments (BTAs), which is a trade measure that levels the playing field between domestic producers that face costly climate measures and foreign producers that face very few. A BTA would put a charge (in the form of a carbon tax) on imported goods equivalent to what these goods would have had to be charged if they had been produced domestically. In the case of exported goods the scheme rebates any paid of carbon taxes to exporters. By doing this, a BTA preserves mitigation of emissions without affecting the international competitiveness of carbon-intensive sectors thereby mitigating carbon leakage incentives (that is, mitigating the incentive of carbon-intensive sectors to relocate production to countries with low environmental standards). For an analysis of BTAs (as Pareto efficient devices) see Keen and Kotsogiannis (2012).[3]

Though—following Keen and Kotsogiannis (2012)—the characterization of a BTA as a Pareto efficient instrument is well understood, it is not entirely clear (though intuition does suggest that they might exist) whether, starting from a distorting initial equilibrium (in emission levels), there exist tariff reforms undertaken unilaterally by a country that increases global welfare. And this is the objective of this chapter. It will be shown that there exists a reform—and one that changes tariffs equi-proportionately—that maximize aggregate welfare.

The rest of this chapter is organized as follows. Section 3.2 describes the model. Section 3.3 introduces (and discusses) the tariffs reforms while Section 3.4 summarizes the results and discusses their policy relevance.

[3] This work builds on the work of Markusen (1975), Baumol and Oates (1988), Krutilla (1991) and Hoel (1996), that identifies trade policy as an instrument that can mitigate emissions in a foreign country.

3.2 Description of the model

The framework is a standard general equilibrium model of international trade (introduced in Chapter 1 and 2) in which there are two countries labeled 'home' and 'foreign'. Home and foreign country's variables are indexed by lower-and upper-case letters, respectively. The economy is a perfectly competitive small open one, thus international prices, w, will be treated parametrically.

In each country there are N tradable commodities. The first traded commodity is used as the numeraire good, with its home and foreign prices being normalized to unity. Throughout the analysis it will be assumed that the numeraire good is untaxed. Pollution is modeled as a by-product of production in the sense that production generates some pollutant, denoted by the N-vector z, for the home, and Z for the foreign country.[4] Total emissions in in the home (foreign) country denoted by $k(K)$ are given by $i'z$ ($i'Z$), where i is the N-vector of 1s (and a prime denotes transposition).

Pollution is transboundary and given by[5]

$$k = K = i'z + i'Z \ . \tag{3.1}$$

In each country there is a representative consumer with preferences represented by the expenditure function $e(u, k, p)$ $(E(U, K, P))$ that gives the minimum expenditure required to achieve utility $\bar{u}$ $(\bar{U})$

4 As noted in Chapters 1 and 2 this is not a restrictive assumption.
5 Notice that one can also introduce (the degree of) externalities across countries. This, however, would add no additional insights.

given pollution k (K) and prices p (P) respectively for each country.

$$e(p,u,k) = \min_{x} \{p'x : u(x,k) \geq \bar{u}\} \ \ ; \ \ E(P,U,K) = \min_{x} \left\{P'X : U(X,K) \geq \bar{U}\right\} \ , \tag{3.2}$$

with, as an envelope property, e_p (E_p) being the vector of compensated demands and e_k (E_K) the consumer's marginal willingness to pay for pollution reduction in terms of the private good. Notice, for later use that, $e_k > 0$ ($E_K > 0$) since pollution is a 'public bad'; a unit of extra consumption of pollution requires by the consumer a positive compensation in terms of the private good.

Home country imposes sector-specific pollution taxes, given by the N-vector s. All revenues collected are returned to the consumer in a lump-sum fashion.

The private sector in the home country is perfectly competitive and characterized by the revenue function

$$r(p,s,v) = \max_{y,z}\{p'y - s'z : (y,z) \in \tau(v)\} \ , \tag{3.3}$$

where $\tau(v)$ is the home country's technology set, v is the vector of endowments, and y denotes the (net) output of tradeable goods. The revenue function in (3.3) gives the maximum revenues generated for given prices p and pollution taxes s.It has the standard properties: It is a convex function, homogeneous of degree one in p and s and (assumed to be) twice continuously differentiable.[6] Given the properties of the revenue function, the matrices r_{pp} and r_{ss} are both positive semi-definite matrices.

6 Notice that implicit in (3.3) is that the private sector can abate environmental discharges by altering production patterns.

Hotelling's lemma implies that, the output vector is given by[7]

$$y = r_p\left(p, s\right) \ , \tag{3.4}$$

whereas the vector of emissions (associated with the production of the N tradeable goods) is given—as an envelope property from (3.3)—by

$$z = -r_s\left(p, s\right) \ . \tag{3.5}$$

Production in the foreign country is described by

$$R(P, S, V) = \max_{Y,Z}\{P'Y - S'Z : (Y, Z) \in T(V)\} \ . \tag{3.6}$$

The foreign country does not impose any pollution-taxes and thus $S = 0$.[8] Following (3.6), as an envelope property, the output and the emissions vector defined, respectively, by

$$Y = R_p\left(P, 0\right) \ ; \quad Z = -R_s(P, 0) \ , \tag{3.7}$$

where P is the foreign country's price vector of the tradeable goods.

The home country uses trade taxes (or subsidies if they are exported)—denoted by the N-vector t— on the tradeable goods with any revenues being returned to the consumer in a lump-sum fashion.

Given the vector of pollution taxes and tariffs, the equilibrium for this economy, assuming it exists,

7 The endowment vectors, being fixed, are being suppressed from what follows.

8 A word of clarification is in order here. One need to worry about the possibility that, with $S = 0$, the private sector generates infinite amount of emissions. Though this might the case appropriate restrictions on the technology can rule this out. Not being central in the analysis, it will be assumed that this indeed the case.

is characterized by

$$e\left(u,k,p\right) = r\left(p,s\right)+t'\left(e_p\left(u,k,p\right)-r_p\left(p,s\right)\right)+s'z\ , \tag{3.8}$$

$$E(U,K,P) = R(P,0)\ , \tag{3.9}$$

$$p = P+t\ , \tag{3.10}$$

$$P = w\ , \tag{3.11}$$

$$k = K=i'z+i'Z=-i'r_s(p,s)-i'R_s\left(P,0\right)\ , \tag{3.12}$$

Equations (3.8) and (3.9) represent, respectively, the budget constraint of the consumer of the home and the foreign country, respectively: It simply says that (for the home country) expenditures given by $e\left(u,k,p\right)$ are equal to GDP, given by $r(p,s)$, plus the pollution-tax and the tariffs revenues, given by $s'z$ and $t'\left(e_p\left(u,k,p\right)-r_p\left(p,s\right)\right)$. No revenues accrue to the foreign country—in the absence of trade and pollution taxes—and so expenditure $E(U,K,P)$ is equal to $R(P,0)$.

Perturbing (3.12), after making use of the fact that—following[9] $dw=0$—$dp=dt$ one obtains[10]

$$dk=dK=-i'r_{sp}dt-i'r_{ss}ds\ . \tag{3.13}$$

Perturbing now equation (3.8)—after making use of (3.4), (3.13) and the fact that $dp=dt$ and also

9 Recall that this is small open economy.

10 Equation (3.13) shows the limitation of fixed international prices w. If international prices could be affected by home country's tariffs and pollution taxes, the home country would be able to affect foreign production directly via international prices w, since they are functions of domestic instruments. To see this notice that, following (3.6), $dK=-i'R_{SP}dw$. Any change in s or t would affect w and so, in turn, K.

$dP = 0$—one obtains

$$e_u(1 - t'm)du = [(e_k i' - t' e_{pk} i' - s')\, r_{sp} - t'\lambda]\, dt + [(e_k i' - t' e_{pk} i' - s')\, r_{ss} - t' r_{ps}]\, ds\ , \qquad (3.14)$$

where $1 - t'm > 0$, with $m = e_{pu}/e_u > 0$, and $\lambda = r_{pp} - e_{pp}$ is a positive semi-definite matrix of home excess compensated supplies.[11]

Equation (3.14) shows, clearly, that home country welfare depends on a number of distortions In particular:

- The terms $e_k i' - t' e_{pk} i' - s'$ gives the deviation of the marginal damage, in the home country, from the pollution-tax vector s. With trade taxes, an increase in pollution affects consumers through two effects: A direct one, and given by $e_k i'$, and an indirect one, and given by $t' e_{pk} i'$, through the trade distortions and so via a change in the compensated demands. If the compensated demands fall because of an increase in pollution, and so $e_{pk} < 0$, then the trade distortion is exacerbated by the pollution.
- The term $t'\lambda$ which gives the effect of changes in the import demand as a consequence of the change in tariffs.

Similarly, pollution taxes have a number of effects on welfare.

- The term $e_k i'$ gives the direct effect (a reduction of pollution which represent a welfare gain) of the tax on pollution.
- The term $t' e_{pk} i'$ gives the indirect effect through the trade distortion.
- The term $t' r_{ps}$ gives the effect of pollution taxes on welfare through tax revenues (since imports changes as a consequence of changes in the policy instrument).

The balance of these effects in equation (3.14) defines the optimal policies of the home country. Clearly, and in the absence of tariffs, the preceding discussion suggests that home country will set pollution taxes, at the optimum level $e_k i = s$. Indeed this is the case. To see this set $t = 0$ and $dt = 0$ in (3.14)

11 $e_u\,(1 - t'm)$ gives the change in the real income, deflated by the tariff multiplier, Nearly (2006). The fact that $1 - t'm > 0$ relates to the stability of the equilibrium (and to the Hatta normality condition).

to obtain

$$e_u du = (e_k i' - s') \, r_{ss} ds \; , \tag{3.15}$$

and so optimality, from the home country's perspective, dictates that the optimal pollution tax is given by—given that r_{ss} is (assumed to be) invertible—$e_k i = s$. To emphasize:

Proposition 3.1 *Optimal policy for the home country dictates that it sets pollution taxes equal to the consumer's marginal willingness to pay for pollution reduction.*

The fact that home country sets $s = e_k i$ is intuitive: Since the home country cannot affect international prices and, therefore, pollution in the foreign country it sets the marginal willingness to pay for a reduction in pollution at home e_k equal to the pollution-tax s.[12]

The analysis turns next to the search for Pareto improving tariff reforms when home country set its pollution taxed at their optimum level.

3.3 Welfare improving tariff reforms

Suppose now that the home country imposes pollution taxes optimally following (3.15). Then, the question is, can we find tariff-reforms that improve global welfare? This is to what we now turn.

Perturbing (3.9), for fixed pollution tax vector s, with $dw = 0$ and using equation (3.13), one

[12] One, of course, might ask whether, starting from an initial situation in which $e_k \neq s$, a pollution tax reform that increases utility in the home country can be implemented. The answer to this is in the affirmative. Consider, for instance, the reform that changes s equiproportionally to its difference from the marginal external damage of pollution that is, $ds = (e_k - s) \, da$ where a is a scalar and $da > 0$. In this case (3.15) reduces to

$$e_u \, (1 - t'm) \, du = (e_k - s)' \, r_{ss} \, (e_k - s) \, da > 0$$

where the inequality sign following from the fact that r_{ss} is a positive semi-definite matrix. This reconfirm the result in Copeland (1994), p.51.

obtains

$$E_U dU = E_K i' r_{sp} dt \ . \tag{3.16}$$

As can be seen from (3.16) foreign welfare is affected by the home country's tariffs but, interestingly, not because tariffs have a price effect on foreign demand but simply because they affect production at home and so pollution in the foreign country (the term $i' r_{sp}$).[13] What (3.16) also shows is the possibility that the foreign country might benefit from a tariff reform in the home country.[14]

Aggregate welfare, following from (3.14) and (3.16) with pollution taxes set to optimum, is given by

$$\delta du + \Delta dU = \left[\left(E_k i' - t' e_{pk} i' \right) r_{sp} - t' \lambda \right] dt \ , \tag{3.17}$$

where $\delta \equiv e_u \left(1 - t' m \right)$ and $\Delta \equiv E_U$. It is now easy to see that the optimal tariff that maximizes global welfare is given by

$$t' \left(s \right) = \left(E_k i' - t' e_{pk} i' \right) r_{sp} \lambda^{-1} \ , \tag{3.18}$$

where $t \left(s \right)$ denotes the dependence of the optimal tariff on pollution distortions. What (3.18) emphasizes is that it is not only distortions via trade (in the sense of changes in the home country's compensated demands, $e_{pk} i' r_{sp} \lambda^{-1}$) that the optimal tariff should account for, but also the foreign country pollution distortions ($E_k i' r_{sp} \lambda^{-1}$), that affect foreign (and so global) utility. Notice that if $r_{sp} = 0$, then the optimal

13 Notice that—as alluded to earlier—if the home country's emissions do not respond to prices, and so $r_{sp} = 0$, then the home country's tariffs will not affect foreign welfare.

14 This will be, for instance, the case if tariffs change according to $dt = E_k i' da$ where a is a scalar. In this case (3.16) reduces to $E_U dU = E_k i' r_{sp} E_k i' da$. The welfare sign of this depends on the structure of the matrix r_{sp}, which cannot be signed without additional assumptions on the structure of technology (see Copeland (1994)), and on the direction of da. All the reform requires is that da taken the same sign of r_{sp}.

tariff, from a world welfare perspective, is zero: The point here being that tariffs cannot affect production decisions at home and, therefore, should not be used; *free trade* is optimal.

The question that now arises is the to what extend one can construct a tariff reform that raise (global) welfare. This is to what we now turn. To answer this it will help re-writing—using (3.18)—aggregate welfare in (3.17) as

$$\delta du + \Delta dU = [t(s) - t]' \lambda dt \, . \tag{3.19}$$

Consider now the scenario of moving tariffs towards their Pareto efficient level in the sense that

$$dt = [t(s) - t] \, da \, , \tag{3.20}$$

with $da > 0$. Substituting (3.20) into (3.19) we have that

$$\delta du + \Delta dU = [t(s) - t]' \lambda [t(s) - t] \, da > 0 \, , \tag{3.21}$$

where the inequality follows from the fact that λ is a positive semi-definite matrix (and $da > 0$). This simple says that if the optimal tariff that maximizes global welfare $t(s)$ is above the existing one t it should be increased. If on the other hand $t(s) < t$ then it should be reduced. To emphasize:

Proposition 3.2 *Starting from any arbitrary tariff distorted equilibrium, with $t \neq t(s)$, and initial pollution taxes set at their second best optimal non-cooperative level $s = e_k i$, then a tariff reform in the sense of (3.20) increases global welfare.*

Proposition 3.2 can be seen as a generalization[15] of Copeland (1994). The difference of the present

[15] For more detailed analysis on the effects of equiproportional distortions on welfare see Dixit (1985) and, in a similar context, Baumol and Oates (1988).

analysis to the one in Copeland (1994) is that here the home country takes a global perspective (as it also receives utility from the foreign country).[16] Intuitively, Proposition 3.2 states that the source of inefficiency, given that international prices are fixed, is not the foreign country but the home one. It is the production of the home country that the reform should be accounting for, and not by how much the foreign country produce and so pollute.

Though the result of Proposition 3.2 is, arguably, insightful it seems to be rather restrictive as it is assumed that pollution taxes have been determined under the assumption that tariff are zero. I now relax this assumption. Suppose that optimal pollution taxes are set at their optimal first best level and so—following (3.14)—at

$$s' = (e_k i' - t' e_{pk} i') + t' r_{ps} r_{ss}^{-1} \ . \tag{3.22}$$

Making use now of the fact that $r(p, s)$ is homogeneous of degree one in p and s we have (following (3.14)) that[17]

$$e_u (1 - t'm) = t' e_{pp} dt \ . \tag{3.23}$$

Suppose now that tariffs change according to $dt = -tda$ for some $da > 0$.(and so uniformly). Then

$$e_u (1 - t'm) = -t' e_{pp} t da > 0 \ , \tag{3.24}$$

where the inequality follows from the fact that e_{pp} is a negative semi-definite matrix.

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16 This, as briefly touched upon in the introductory section, relates to border tax adjustments. It is the direction of the reform, and not of the determination of the actual tariff that is the concern here.

17 This implies that $r_{pp} p + r_{ps} s = 0$ and $r_{sp} p + r_{ss} s = 0$, and so $r_{ps} r_{ss}^{-1} r_{sp} = r_{pp}$.

Turning now to global welfare which, following from (3.16) and (3.23), is given by

$$\delta du + \Delta dU = \left(E_k i' r_{sp} + t' e_{pp}\right) dt \ . \tag{3.25}$$

the optimal tariff is given by

$$t'(s) = -E_k i' r_{sp} e_{pp}^{-1} \ , \tag{3.26}$$

which upon close inspection—and in contrast to equation (3.18)—it reveals that it is independent of the home country's pollution distortion.

Consider now an equiproportional movement of tariffs towards their optimum level, in the sense that

$$dt = -\left[t - t(s)\right] da \ , \tag{3.27}$$

for a scalar $da > 0$. Global welfare can then be written as

$$\delta du + \Delta dU = -\left[t - t(s)\right]' e_{pp} \left[t - t(s)\right] da > 0 \ . \tag{3.28}$$

We so have that:

Proposition 3.3 *Starting from any arbitrary tariff distorted equilibrium, with $t \neq t(s)$, and assuming that pollution taxes are set at their first best optimal level, then a home country's tariff reform of the form of (3.27) is Pareto improving.*

3.4 Concluding remarks

This paper has investigated the existence of, starting from an arbitrary tariff distorted equilibrium, potential Pareto improving tariff reforms (or a particular type). It has shown that within small open economies, and in the presence of transboundary pollution, the source of inefficiency of the environmental quality is driven only through the level of production of the home country. It is this production that the home country's tariff reform targets to reduce. A reduction in home production not only benefits the home country (by having less emissions) but also benefits the foreign country through, again, a reduction in harmful emissions.

The limitations of the chapter suggest avenues for future research. International prices have been (conveniently) kept fixed and as a consequence the home country cannot influence foreign production abroad. It would be interesting (and, of course, more challenging) to allow for the home country to be a large open economy (as in Turunen-Red and Woodland. (2004) and Keen and Kotsogiannis (2012) and, therefore, be able to influence the terms of trade (and the comparative advantage in the production of goods) of the foreign country. This will be consistent with the current rhetoric in favour of border tax adjustments.

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Chapter 4 Pareto-efficient climate and trade policies in the presence of non-tradeable goods

4.1 Introduction

In a recent contribution Keen and Kotsogiannis (2012) have characterized Pareto-efficient environmental and trade policies. They have shown that environmental policies take a Pigovian-adjusted form (with weights being the social marginal utilities of income), whereas trade policies, in the presence of lump sum transfers (or if a rank condition in the matrix of global exports holds), are redundant (and they can be normalized away). In the absence of lump sum taxes they have shown that, while carbon taxes still follow a Pigovian form (with equal weights), tariffs now play a role in redistributing income across countries. These results, however, are derived within a model in which non-tradeable goods—arguably a realistic feature of any economic environment—are absent. The objective of this chapter is to relax this assumption. In particular, this chapter asks: Does the existence of non-tradeable goods alter the characterization of Pareto-efficient environmental (and trade policies) derived from a model with tradeable goods only? The answer to this, as it will be shown shortly below, is that it *does not*. Even with non-tradeable goods present, Pareto-efficient environmental policy dictates that, in the presence of lump sum taxes, carbon taxes have a Pigouvian form and they are uniform across all sectors (including those of non-tradeable goods) and countries, while in the absence of lump sum taxes, they are uniform across all sectors in a given country but not across countries.

The plan of the chapter is as follows. Section 4.2 sets out the background against the analysis is conducted. Section 4.3, then, derives the Pareto-efficient carbon tax and tariff policies. Finally, Section 4.4 briefly concludes.

4.2 Description of the model

The model is essentially that of Keen and Kotsogiannis (2012) appropriately modified to include non-tradeable goods. There are J countries, indexed by the superscript j, each of which produces $M = T + N$ goods: T of these goods are tradeable and N are non-tradeable. The T tradeable goods are traded at an T-vector of world prices given by $p_T \gg 0$.[1] The price vector of non-tradeable goods in country j is denoted by $p_N^j \gg 0$.

International trade is subject to trade taxes (or subsidies), the vector of which in country j is denoted by τ^j. The commodity price vector of the tradeable goods in country j is thus given by the T-vector $p_T^j = p_T + \tau^j$. The model is very general in allowing for all types of trade taxes and subsidies. If $\tau_i^j > 0$ ($\tau_i^j < 0$) and commodity i is being imported by country j, then τ_i^j is an import tariff (import subsidy); and if $\tau_i^j > 0$ ($\tau_i^j < 0$) and commodity i is being exported by country j then τ_i^j is an export subsidy (export tax). Trade policies are assumed to be consistent with most-favored nation rules.

Within each country there is a perfectly competitive private production sector. Producers in country j use factor endowments, denoted by vector v^j, to produce the M-vector y^j of commodities. In doing so, the production of each commodity generates some pollutant (such as carbon emissions), with the M-

[1] The following convention is used: If $x = (x_1, ..., x_N)$ then $x \gg 0$ means $x_n > 0$ for all $n = 1, ..., N$; $x > 0$ means $x_n \geq 0$ for all $n = 1, ..., N$ and at least one $x_n \neq 0$; and $x \geq 0$ means $x_n \geq 0$ for all $n = 1, ..., N$.

vector z^j denoting emissions produced by the M commodities in country j. Total emissions in country j are thus given by $\iota' z^j$, where ι is the M-vector of 1s (the unit vector) and a prime indicates transposition. Each national government may impose carbon taxes on the emissions from each commodity (sector), the M-vector of carbon taxes given by s^j. Pollution taxes are so sector-specific.

Global emissions are therefore given by[2]

$$k = \iota' \sum_{j=1}^{J} z^j \ . \tag{4.1}$$

The production sector in country j is perfectly competitive and characterized by a revenue function[3]

$$r^j(p^j, s^j, v^j) = \max_{y^j,\ z^j}\{p^{j\prime} y^j - s^{j\prime} z^j \quad : \quad f^j(y^j, z^j, v^j) \leq 0\} \ , \tag{4.2}$$

where $f^j(\cdot)$ is the implicit production possibility frontier in country j. Notice—following from (4.2), and as an envelope property—that the net output $M-$vector, y^j, and the vector of emissions, z^j, are given by

$$r^j_{p_M}(p^j, s^j, v^j) \ = \ y^j \ , \tag{4.3}$$

$$r^j_s(p^j, s^j, v^j) \ = \ -z^j \ . \tag{4.4}$$

2 One could allow for k to be a vector of pollutants by defining this to be equal to $\sum_{j=1}^{J} z^j$. The present framework can be straightforwardly modified to allow for this possibility. This, however, will not generate any additional insights (the only difference in this case will be with the characterization, and structure, of Pareto-efficient carbon-taxes).

3 The revenue function has the standard properties of homogeneity, convexity and differentiability. For the properties of the revenue function see Dixit and Norman (1980) and Woodland (1982).

The consumption sector in country j is characterized by the expenditure function

$$e^j(p^j, u^j, k) = \min_{x^j}\{p^{j\prime}x^j : U^j(x^j) \geq u^j\} \ , \tag{4.5}$$

where $U^j(x^j)$ is the utility attained by consuming vector x^j of commodities. The expenditure function is concave and linearly homogeneous in prices, increasing in utility, and assumed to be twice continuously differentiable. Notice that pollution k affects utility (presumably negatively). Shephard's lemma gives the M-vector of compensated demands, $e^j_{p_M}(p^j, u^j)$.

It is convenient to define the net expenditure function in country j as[4]

$$S^j(p^j, s^j, u^j, k) \equiv e^j(p^j, u^j, k) - r^j(p^j, s^j, v^j) \ . \tag{4.6}$$

The net expenditure function has the useful derivative properties that the vector of compensated import functions, denoted by $m^j_T(\cdot)$, is given by

$$m^j_T\left(p^j, s^j, v^j, u^j, k\right) \equiv S^j_{p_T}(p^j, s^j, v^j, u^j, k) = e^j_{p_T}(p^j, u^j, k) - r^j_{p_T}(p^j, s^j, v^j) \ , \tag{4.7}$$

where $e^j_{p_T}$ denotes the T-vector of compensated demands for the tradeable goods. Similarly, $r^j_{p_T}$ denotes the net output T-vector of the tradeable goods. The vector of emissions produced by country j is given by[5]

$$z^j\left(p^j, s^j, v^j, k\right) \equiv S^j_s(p^j, s^j) = -r^j_s(p^j, s^j) \ . \tag{4.8}$$

4 The function $S^j(\cdot)$ has the properties of the underlying expenditure and revenue functions.

5 In (4.8) only the arguments of the revenue function are involved, so the argument u^j has been removed from the function S^j_s.

The vector of non-tradeable goods is given by

$$m_N^j\left(p^j, s^j, v^j, u^j, k\right) \equiv S_{p_N}^j(p^j, s^j, v^j, u^j, k) = e_{p_N}^j(p^j, u^j) - r_{p_N}^j(p^j, s^j, v^j) = 0\ . \tag{4.9}$$

Without loss of generality, the first commodity of the tradeable goods is taken as the numeraire, with unit world price, and international trade in this commodity is assumed to be untaxed by any country, so $p_1^j = 1$ and $\tau_1^j = 0$ for all $j = 1, ..., J$. For notational convenience, the price and trade tax vectors will be partitioned accordingly as

$$p_T' = (1, q') \quad ; \quad p_T^{j\prime} = (1, q^{j\prime}) \quad ; \quad q^{j\prime} = q' + \sigma^{j\prime} \quad ; \quad \tau^{j\prime} = (0, \sigma^{j\prime})\ , \tag{4.10}$$

and so domestic prices are given by

$$p_M^{j\prime} = (p_T^j, p_N^j)' = \left((1, q^{j\prime}), p_N^{j\prime}\right)\ . \tag{4.11}$$

The equilibrium conditions for the world economy can be compactly expressed as[6]

$$p_T' S_{p_T}^j\left(p^j, s^j, u^j, k\right) + b^j \ = \ 0,\ j = 1, ..., J\ , \tag{4.12}$$

$$\sum_{j=1}^{J} S_q^j\left(p^j, s^j, u^j\right) \ = \ 0\ , \tag{4.13}$$

$$\iota' \sum_{j=1}^{J} S_s^j(p^j, s^j) \ = \ k\ , \tag{4.14}$$

6 The vector of endowments v^j, since it is fixed, it will be suppressed throughout.

$$\sum_{j=1}^{J} b^j = 0 \,, \tag{4.15}$$

$$S^j_{p_N}(p^j, s^j, u^j, k) = 0 \,,\ j = 1, ..., J \,, \tag{4.16}$$

and S^j_q denotes the net expenditure function for the $T-1$ tradeable goods in country j. It is the presence of equation (4.16) that is central to the analysis here.

The J equations in (4.12) are the consumers' budget constraints: They simply state that the balance of trade deficit (value of net imports at world prices) plus any international transfers to (from) country j must be equal to zero.[7] The $T-1$ equations in (4.13) are the world market equilibrium conditions for non-numeraire tradeable commodities. Equation (4.14) specifies that global emissions are the sum of emissions produced by the J countries. Condition (4.15) requires that the sum of international transfers

[7] There is an alternative way of writing this. The budget constraint of the consumer in country j states that the expenditure $e^j(\cdot)$ is equal to income originating from production, given by $r^j(p^j, s^j)$, plus any revenues transferred from the government to consumers, that amount to $\tau^{j\prime} m^j_T\left(p^j, s^j, v^j(k), u^j\right) + s^{j\prime} z^j + p^\prime b^j$. So

$$e^j(\cdot) = r^j\left(p^j, s^j\right) + \tau^{j\prime} m^j_T\left(p^j, s^j, v^j(k), u^j\right) + s^{j\prime} z^j + b^j.$$

Since $S^j(\cdot) = e^j(\cdot) - r^j(\cdot)$, then

$$S^j(\cdot) = \tau^{j\prime} m^j_T\left(p^j, s^j, v^j(k), u^j\right) + s^{j\prime} z^j + b^j.$$

Using the properties of $S^j(\cdot)$, we have that

$$S^j = p^j S^j_{p_M} + s^j S^j_s,$$

and so

$$p^{j^\prime} S^j_{p_M} + s^j S^j_s = \tau^{j\prime} m^j_T\left(p^j, s^j, v^j, u^j\right) + s^{j\prime} z^j + b^j,$$

which upon simpliying it gives

$$p^\prime_T S^j_{p_T}\left(p^j, s^j, u^j\right) + p^{j\prime}_N S_{p_N}\left(p^j, s^j, u^j\right) + b^j = 0.$$

Since $S^j_{p_N} = 0$ then

$$p^\prime_T S^j_{p_T}\left(p^j, s^j, u^j\right) + b^j = 0.$$

be zero. Equation (4.16) are the market clearing conditions for the non-tradeable goods.

Given the tariff vectors τ^j, $j = 1, ..., J$, and the carbon tax vectors s^j, $j = 1, ..., J$ and the vector $b = (b^1, ..., b^J)'$ of international transfers satisfying (4.15), the national budget constraints (4.12), the market equilibrium conditions (4.13), the global emissions equation (4.14), and the market clearing for non tradeable goods (4.16) may be solved for the competitive equilibrium world price vector for tradeable commodities, p_T, the equilibrium price vector in country j of the non-tradeable goods p_N^j, the level of global emissions, k, and the vector of national utility levels, $u = (u^1, ..., u^J)'$. The existence of a competitive equilibrium solution with $p_M^j \gg 0$ is assumed.

The differential comparative static system is therefore

$$Adu + Bdq + C_T d\widehat{q} + C_N dp_N + Dds + Edk + Fdb = 0 \ , \tag{4.17}$$

where the matrices A, B, C_T, C_N, D, E and F are defined by

$$Adu \equiv \begin{bmatrix} p_T' S_{p_T u}^1 & 0 & \cdots & 0 \\ 0 & p_T' S_{p_T u}^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & \cdots & p_T' S_{p_T u}^J \\ S_{qu}^1 & S_{qu}^2 & \cdots & S_{qu}^J \\ 0 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ S_{p_N u}^1 & 0 & \cdots & 0 \\ 0 & S_{p_N u}^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & \cdots & S_{p_N u}^J \end{bmatrix} \begin{bmatrix} du^1 \\ du^2 \\ \vdots \\ du^J \end{bmatrix} ,$$

$$B dq \equiv \begin{bmatrix} S_q^{1\prime} \\ S_q^{2\prime} \\ \vdots \\ S_q^{J\prime} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} dq \;\;,^{8}$$

$$C_T d\widehat{q} \equiv \begin{bmatrix} p_T' S^1_{p_T q} & 0 & \cdots & 0 \\ 0 & p_T' S^2_{p_T q} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & p_T' S^J_{p_T q} \\ S^1_{qq} & S^2_{qq} & \cdots & S^J_{qq} \\ \iota' S^1_{sq} & \iota' S^2_{sq} & \cdots & \iota' S^J_{sq} \\ 0 & 0 & \cdots & 0 \\ S^1_{p_N q} & 0 & \cdots & 0 \\ 0 & S^2_{p_N q} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & S^J_{p_N q} \end{bmatrix} \begin{bmatrix} dq^1 \\ dq^2 \\ \vdots \\ dq^J \end{bmatrix} \;\;,$$

$$C_N dp_N \equiv \begin{bmatrix} p_T' S^1_{p_T p_N} & 0 & \cdots & 0 \\ 0 & p_T' S^2_{p_T p_N} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & p_T' S^J_{p_T p_N} \\ S^1_{q p_N} & S^2_{q p_N} & \cdots & S^J_{q p_N} \\ \iota' S^1_{s p_N} & \iota' S^2_{s p_N} & \cdots & \iota' S^J_{s p_N} \\ 0 & 0 & \cdots & 0 \\ S^1_{p_N p_N} & 0 & \cdots & 0 \\ 0 & S^2_{p_N p_N} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & S^J_{p_N p_N} \end{bmatrix} \begin{bmatrix} dp_N^1 \\ dp_N^2 \\ \vdots \\ dp_N^J \end{bmatrix} \;\;,$$

[8] Notice that the vector q is a—following the normalization of prices—$T-1$-vector.

$$Dds \equiv \begin{bmatrix} p_T' S_{p_T s}^1 & 0 & \cdots & 0 \\ 0 & p_T' S_{p_T s}^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & \cdots & p_T' S_{p_T s}^J \\ S_{qs}^1 & S_{qs}^2 & \cdots & S_{qs}^J \\ \iota' S_{ss}^1 & \iota' S_{ss}^2 & \cdots & \iota' S_{ss}^J \\ 0 & 0 & \cdots & 0 \\ S_{p_N s}^1 & 0 & \cdots & 0 \\ 0 & S_{p_N s}^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & S_{p_N s}^J \end{bmatrix} \begin{bmatrix} ds^1 \\ ds^2 \\ \vdots \\ ds^J \end{bmatrix},$$

$$Edk \equiv \begin{bmatrix} p_T' S_{p_T k}^1 \\ p_T' S_{p_T k}^2 \\ \vdots \\ p_T' S_{p_T k}^J \\ \sum_{j=1}^{J} S_{q_T k}^j \\ -1 \\ 0 \\ S_{p_N k}^1 \\ S_{p_N k}^2 \\ \vdots \\ S_{p_N k}^J \end{bmatrix} dk \,,$$

$$Fdb \equiv \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \\ 0 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ -1 & -1 & \cdots & -1 \\ 0 & 0 & \cdots & 0 \\ \vdots & 0 & \cdots & \vdots \\ \vdots & \vdots & 0 & \vdots \\ 0 & 0 & \cdots & 0 \end{bmatrix} \begin{bmatrix} db^1 \\ db^2 \\ \vdots \\ db^J \end{bmatrix} .$$

To characterize Pareto optimality of the initial equilibrium it proves convenient to use Tucker's

Theorem of the Alternative (Mangasarian, 1969, p. 34). Tucker's Theorem of the Alternative states that either the system in (4.17) has a solution with $du > 0$ (where $du > 0$ is a semipositive vector with, that is, $du^j \geq 0$ for all $j = 1, ..., J$ and $du \neq 0$) for some perturbation $(dq, d\widehat{q}, dp_N, ds, dk, db)$—so that the initial equilibrium is Pareto *inefficient*—or there is a vector $y = (y_1, y_2, y_3, y_4, y_5) \in R^{J+(T-1)+1+T+JN}$ (where $y_1 = \left(y_1^1, ..., y_1^J\right)' \in R^J$, $y_2 = \left(y_2^2, ..., y_2^T\right)' \in R^{T-1}$, $y_4 = \left(y_4^1, ..., y_4^T\right)' \in R^T$ $y_5 = \left(y_5^1, ..., y_5^J\right)' \in R^{JN}$ with $y_5^j = \left(y_5^{j1}, ..., y_5^{jN}\right) \in R^N$) such that

$$y'[B, C_T, C_N, D, E, F] = 0, \tag{4.18}$$

$$y'A \ll 0, \tag{4.19}$$

in which case the initial equilibrium is Pareto efficient. The analysis now proceeds to the derivation of Pareto efficient climate and trade policies (the details are relegated to the Appendix).

4.3 Pareto-efficient climate and trade policies

This section considers the characterization of Pareto-efficient carbon tax and trade tax policies. If a world economy has such policies then it is not possible to alter any carbon or trade taxes to make one consumer better off, starting at the initial equilibrium, without making some other consumer worse off. That is, a Pareto improvement in policy choice is not possible implying that the initial equilibrium and tax policy settings are Pareto *efficient*. In the current framework, the following results establish the two key features of *any* Pareto efficient allocation.

Proposition 4.1 *In the presence of lump sum transfers across countries (and the presence of both tradeable and non-tradeable goods), Pareto efficiency requires that in every country* $j = 1, ..., J$:

(a) carbon taxes are set at $s^j = \left(\sum_{i=1}^{J} S_k^i\right)\iota$*, so they are uniform across production sectors within a country and also uniform across countries,*

(b) trade tax vectors are equal, $\sigma^j = \sigma$, $j = 1, ..., J$*, implying that domestic price vectors of the tradeable goods are all equal*

(c) the prices of non-tradeable goods are country-specific satisfy $p_N^{j\prime} = y_5^{j\prime}/y_4$.

Proposition 4.1 states the Pareto efficient allocation of the available to the social planer instruments. The social planer chooses carbon taxes and goods prices either directly, as in the case of non-tradeable goods, or indirectly, as in the case of tradeable goods through the choice of trade taxes. According to Proposition 4.1 Pareto efficiency requires that—even in the presence of non-tradeable goods—each country sets a Pigovian carbon tax in each of the M sector to equate the marginal cost of an extra unit of carbon emissions, s^j, to the marginal global damage that the extra unit of emissions causes through climate change, $\sum_{i=1}^{J} S_k^i \iota$. The uniformity of carbon taxes within a country follows from the fact that carbon emissions from each sector contribute, at the margin, equally to the stock of carbon in the atmosphere and, hence climate change, no matter where they are produced taking into account general equilibrium effects upon prices and tax receipts. Part (b) of the Proposition 4.1, implies equality of domestic prices (of the tradeable goods) and the collinearity of the tariff vectors across all countries. The importance of this is in emphasizing that—in the presence of lump sum transfers—production efficiency (for the tradeable goods) is part of a Pareto efficient allocation. To see this, recall that producer prices in country j are $p_T^{j\prime} = (1, q') + (0, \sigma^{j\prime})$ and so with $\sigma^j = \sigma$ for $j = 1, ..., J$, it is the case that $p_T^{j\prime} = p_T'$ for all countries j. Parts (c) of the Proposition 4.1 states the Pareto efficient country-specific prices of the non-tradeable goods. Notice that, if it happens that $y_5^j = y_5$—and so the shadow value of non-tradeable goods is the same across countries[9]—then the price vectors for non-tradeable goods are collinear across countries (with a degree of collinearity $1/y_4$). Clearly, as Proposition 4.1 shows, the presence of the non-tradeable goods does not change the uniformity structure of carbon taxes within and across countries nor the collinearity of the trade tax vectors. This is, perhaps, not surprising (once seen) as—with redistribution being taken care of by lump sum transfers and carbon taxes being uniform across all M sectors—non-tradeable goods have no additional role to play, at a Pareto efficient allocation, in pollution policies.

But what now if international lump sum transfers are unavailable. In this case, it is the case that:

Proposition 4.2 *In the absence of international lump sum transfers (and assuming that the substitution matrix for each j country has maximal rank), Pareto efficiency requires that in every country $j = 1, ..., J$:*

(a) carbon taxes are set such that $y_1^j s^i = \left(\sum_{i=1}^J y_1^i S_k^i\right) \iota$, where y_1^j is a scalar, and so carbon taxes are uniform across production sectors within a country but different across countries in the sense that for any countries j and i they satisfy $s^j = \alpha^{ij} s^i$, where $\alpha^{ij} \equiv y_1^i / y_1^j$, and

(b) trade tax vectors are collinear across countries in the sense that $\sigma^j = \alpha^{ij}\sigma^i$, $j = 1, ..., J$, implying that domestic price vectors are also collinear across countries

(c) the prices of the non-tradeable goods are country-specific and satisfy $p_N^{j\prime} = y_5^{j\prime} / y_1^j$.

Part (a) of the proposition simply says that in a Pareto efficient allocation carbon taxation reflects

9 There is no reason, of course, to suppose that this will be the case.

the global changes in utility, taking into account the cross country income implications of this (through the scalar multipliers y_1^j). Part (b) is more striking, the idea here being that the social planner uses tariffs (and so the prices of the tradeable goods) as a redistribution device. Consistently with Keen and Kotsogiannis (2012), there is generally global production inefficiency for the tradeable goods in the allocations characterized by Proposition 4.2. Though increasing the net output of some good in some country without reducing the net output of any other good or increasing emissions requires that both producer prices and carbon taxes be equalized across countries, the proposition shows that Pareto efficiency allows for trade taxes, and hence domestic prices, to differ internationally. Pareto efficiency does not require that $\sigma^j = 0$—all that matters is the collinearity of production price vectors (and so global production inefficiency occurs). Turning now to non-tradeable goods (and their prices) one notices that these prices also reflect the redistribution motive of the central planner. Clearly, in this case (and even if the shadow prices of the non-tradeable goods where the same across countries in the sense that $y_5^j = y_5$) non-tradeable price vector will not be collinear. What Proposition 4.2 implies is intuitive: The central planer implicitly chooses goods prices either directly, in the case of non-tradable goods, or indirectly, in the case of tradable goods, through tariffs to correct any distributional misallocations. The presence of non-tradable goods does not impede the central planner of imposing the Pigovian carbon taxes (of part (a) of Proposition 4.2).

4.4 Concluding remarks

This chapter has extend Keen and Kotsogiannis (2012) to show that the presence of non-tradeable goods does not affect the characterization (at a Pareto-efficient allocation) of Pareto-efficient carbon taxes.

Appendix A

Proof of Proposition 4.1:

Given the differentiability assumptions concerning the expenditure and revenue functions the system—re-written here again for convenience—(4.12), (4.13), (4.14), (4.15) and (4.16)

$$p_T' S^j_{p_T}\left(p^j, s^j, u^j, k\right) + b^j = 0,\ j = 1, ..., J, \tag{A.1}$$

$$\sum_{j=1}^{J} S^j_q\left(p^j, s^j, u^j\right) = 0, \tag{A.2}$$

$$\iota' \sum_{j=1}^{J} S^j_s(p^j, s^j) = k, \tag{A.3}$$

$$\sum_{j=1}^{J} b^j = 0, \tag{A.4}$$

$$S^j_{p_N}(p^j, s^j, u^j, k) = 0,\ j = 1, ..., J \tag{A.5}$$

Equations (4.18) and (4.19) are necessary and sufficient conditions for Pareto optimality in the present model.

The equations in (4.18) and (4.19) can be readily shown to be expressed as

$$
\begin{aligned}
y'A &= \left[y_1^j p_T' S_{p_T u}^j + y_2' S_{qu}^j + y_5^{j\prime} S_{p_N u}^j, \quad j = 1, ..., J\right] \ll 0', && \text{(A.6)} \\
y'B &= \left[\sum_{j=1}^{J} y_1^j S_q^{j\prime}\right] = y_1' S_q' = 0', && \text{(A.7)} \\
y'C_T &= \left[y_1^j p_T' S_{p_T q}^j + y_2' S_{qq}^j + y_3 \iota' S_{sq}^j + y_5^{j\prime} S_{p_N q}^j, \quad j = 1, ..., J\right] = 0', && \text{(A.8)} \\
y'C_N &= \left[y_1^j p_T' S_{p_T p_N}^j + y_2' S_{qp_N}^j + y_3 \iota' S_{sp_N}^j + y_5^{j\prime} S_{p_N p_N}^j, \quad j = 1, ..., J\right] = 0', && \text{(A.9)} \\
y'D &= \left[y_1^j p_T' S_{p_T s}^j + y_2' S_{qs}^j + y_3 \iota' S_{ss}^j + y_5^{j\prime} S_{p_N s}, \quad j = 1, ..., J\right] = 0', && \text{(A.10)} \\
y'E &= \sum_{j=1}^{J} y_1^j p_T' S_{p_T k}^j + \sum_{j=1}^{J} y_2' S_{qk}^j - y_3 + \sum_{j=1}^{J} y_5^{j\prime} S_{p_N k}^j = 0, && \text{(A.11)} \\
y'F &= \left[y_1^j - y_4, \quad j = 1, ..., J\right] = 0, && \text{(A.12)}
\end{aligned}
$$

where we follow the convention to denote matrices with elements for each $j = 1, ..., J$ in the square brackets.

Notice that combining (A.8) and (A.9) we have that

$$
y_1^j p_T' \left[S_{p_T q}^j | S_{p_T p_N}^j\right] + y_2' \left[S_{qq}^j | S_{qp_N}^j\right] + y_3 \iota' \left[S_{sq}^j | S_{sp_N}^j\right] + y_5^{j\prime} \left[S_{p_N q}^j | S_{p_N p_N}^j\right] = 0', \qquad \text{(A.13)}
$$

where

$$\left[S^j_{p_T q}|S^j_{p_T p_N}\right]_{T\times(M-1)}, \tag{A.14}$$

$$\left[S^j_{qq}|S^j_{qp_N}\right]_{(T-1)\times(M-1)}, \tag{A.15}$$

$$\left[S^j_{sq}|S^j_{sp_N}\right]_{M\times(M-1)}, \tag{A.16}$$

$$\left[S^j_{p_N q}|S^j_{p_N p_N}\right]_{N\times(M-1)}. \tag{A.17}$$

(A.13) can be re-written as

$$y^j_1 p'_T\left[S^j_{p_T q}|S^j_{p_T p_N}\right]+(0,y'_2)\left[S^j_{p_T q}|S^j_{p_T p_N}\right]+y_3\iota'\left[S^j_{sq}|S^j_{sp_N}\right]+y^{j\prime}_5\left[S^j_{p_N q}|S^j_{p_N p_N}\right]=0',$$

and so, after defining

$$\rho'\equiv y_4 p'_T+(0,y'_2), \tag{A.18}$$

a $1\times T$ vector, as

$$\left(\rho',y^{j\prime}_5\right)\left[\begin{array}{c} S^j_{p_T q}|S^j_{p_T p_N} \\ S^j_{p_N q}|S^j_{p_N p_N}\end{array}\right]+y_3\iota'\left[S^j_{sq}|S^j_{sp_N}\right]=0'. \tag{A.19}$$

Equation (A.19) has used the fact that equation (A.12) implies that $y^j_1 = y_4$ for all $j = 1,...,J$ and so $y_1 = y_4\iota$ (where ι is the unit vector).The implication of this is that the marginal social utilities of income—given by y^j_1 for country j—are the same across all countries.

Following (A.6) we also have that

$$y'A = \left[\left(\rho, y_5^j\right)'\left(S_{p_M u}^j\right),\ j = 1, ..., J\right] \ll 0', \tag{A.20}$$

where $S_{p_M u}^j$ is an $M-1$-vector. Similarly, following equation (A.10) we have that

$$\begin{aligned} y'D &= \left[y_1^j p_T' S_{p_T s}^j + y_2' S_{qs}^j + y_3 \iota' S_{ss}^j + y_5^{j\prime} S_{p_N s}, \qquad j = 1, ..., J\right] = 0', & \text{(A.21)} \\ &= \left(\rho, y_5^j\right)' \begin{bmatrix} S_{p_T s}^j \\ S_{p_N s}^j \end{bmatrix} + y_3 \iota' S_{ss}^j, \qquad j = 1, ..., J = 0'. & \text{(A.22)} \end{aligned}$$

Equations (A.6)-(A.11) may therefore be re-expressed as

$$\begin{aligned} y'A &= \left[\left(\rho, y_5^j\right)' S_{pu}^j,\ j = 1, ..., J\right] \ll 0', & \text{(A.23)} \\ y'B &= \left[y_4 \sum_{j=1}^{J} S_q^{j\prime}\right] = 0', & \text{(A.24)} \\ y'C &= \left[\left(\rho, y_5^j\right)' \begin{bmatrix} S_{p_T q}^j | S_{p_T p_N}^j \\ S_{p_N q}^j | S_{p_N p_N}^j \end{bmatrix} + y_3 \iota' \left[S_{sq}^j | S_{sp_N}^j\right],\ j = 1, ..., J\right] = 0', & \text{(A.25)} \\ y'D &= \left[\left(\rho, y_5^j\right)' \begin{bmatrix} S_{p_T s}^j \\ S_{p_N s}^j \end{bmatrix} + y_3 \iota' S_{ss}^j,\ j = 1, ..., J\right] = 0', & \text{(A.26)} \\ y'E &= \sum_{j=1}^{J} \left(\rho, y_5^j\right) \begin{bmatrix} S_{p_T s}^j \\ S_{p_N s}^j \end{bmatrix} - y_3 = 0. & \text{(A.27)} \end{aligned}$$

Following from (A.25) and (A.26), equations $y'C = 0'$ and $y'D = 0'$ may be combined together as

$$\left(\left(\rho', y_5^j\right), \quad y_3 \iota'\right) \left(\begin{matrix} \begin{bmatrix} S_{p_T q}^j | S_{p_T p_N}^j \\ S_{p_N q}^j | S_{p_N p_N}^j \end{bmatrix} & \begin{bmatrix} S_{p_T s}^j \\ S_{p_N s}^j \end{bmatrix} \\ \left[S_{sq}^j | S_{sp_N}^j\right] & \left[S_{ss}^j\right] \end{matrix} \right) = (0, \ \ 0)'. \tag{A.28}$$

Denoting

$$
\begin{aligned}
S^j_{p\hat{p}} &\equiv \left[\begin{array}{c} S^j_{p_T q} | S^j_{p_T p_N} \\ S^j_{p_N q} | S^j_{p_N p_N} \end{array} \right], \\
S^j_{s\hat{p}} &\equiv \left[S^j_{sq} | S^j_{s p_N} \right], \\
S^j_{ps} &\equiv \left[\begin{array}{c} S^j_{p_T s} \\ S^j_{p_N s} \end{array} \right],
\end{aligned}
$$

then (A.28) is equal to

$$
\left(\left(\rho', y^j_5 \right), \ \ y_3 \iota' \right) \left(\begin{array}{cc} S^j_{p\hat{p}} & S^j_{ps} \\ S^j_{s\hat{p}} & S^j_{ss} \end{array} \right) = (0, \ \ 0)'. \tag{A.29}
$$

Homogeneity of the net expenditure function in price vector $(p^{j\prime}, s^{j\prime})$ implies that[1]

$$
\left(p^{j\prime}, \ \ s^{j\prime} \right) \left(\begin{array}{cc} S^j_{p\hat{p}} & S^j_{ps} \\ S^j_{s\hat{p}} & S^j_{ss} \end{array} \right) = (0, \ \ 0)' \tag{A.30}
$$

holds as an identity.

1 This follows from the fact that $S^j_p \left(p^j, s^j \right)$ and $S^j_s \left(p^j, s^j \right)$ are homogeneous of degree zero. This implies that

$$
\begin{aligned}
S^j_{pp} p^{j\prime} + S^j_{ps} s^{j\prime} &= 0' \\
S^j_{sp} p^{j\prime} + S^j_{ss} s^{j\prime} &= 0'.
\end{aligned}
$$

Combining, we have that

$$
\left[\begin{array}{cc} S^j_{pp} & S^j_{ps} \\ S^j_{sp} & S^j_{ss} \end{array} \right] \left[\begin{array}{c} p^{j\prime} \\ s^{j\prime} \end{array} \right] = \left[\begin{array}{c} 0' \\ 0' \end{array} \right],
$$

and so, upon transposing,

$$
\left[\begin{array}{cc} p^{j\prime} & s^{j\prime} \end{array} \right] \left[\begin{array}{cc} S^j_{pp} & S^j_{ps} \\ S^j_{sp} & S^j_{ss} \end{array} \right]' = \left[\begin{array}{cc} 0' & 0' \end{array} \right].
$$

Notice now that (A.29) can be written as

$$\left(\left(y_4 p_T' + (0, y_2'), y_5^j\right), \quad y_3 \iota'\right) \begin{pmatrix} S_{p\hat{p}}^j & S_{ps}^j \\ S_{s\hat{p}}^j & S_{ss}^j \end{pmatrix} = (0, \quad 0)', \tag{A.31}$$

whereas (A.30) can be written as (after multiplying by y_4)

$$\left((y_4 p_T' + y_4(0, \sigma^{j\prime}), y_4 p_N^{j\prime}), \quad y_4 s^{j\prime}\right) \begin{pmatrix} S_{p\hat{p}}^j & S_{ps}^j \\ S_{s\hat{p}}^j & S_{ss}^j \end{pmatrix} = (0, \quad 0)'. \tag{A.32}$$

Subtracting one from the other we have that

$$\left(\left(\left(y_4 \sigma^{j\prime} - y_2'\right), y_4 p_N^j - y_5^j\right), \quad \left(y_4 s^{j\prime} - y_3 \iota'\right)\right) \begin{pmatrix} S_{p\hat{p}}^j & S_{ps}^j \\ S_{s\hat{p}}^j & S_{ss}^j \end{pmatrix} = (0, \quad 0)'. \tag{A.33}$$

This implies that

$$\sigma^{j\prime} = y_2'/y_4, \tag{A.34}$$

$$s^{j\prime} = y_3 \iota'/y_4, \tag{A.35}$$

$$p_N^{j\prime} = y_5^{j\prime}/y_4. \tag{A.36}$$

Assuming that the substitution matrix for each country has maximal rank, $(p^{j\prime}, s^{j\prime})$ is the only vector (up to a factor of proportionality) satisfying the equality in equation (A.30).

Consequently, it must be the case that

$$\left(\left(\rho', y_5^j\right), \quad y_3 \iota'\right) = \left(p^{j\prime}, s^{j\prime}\right)$$

(up to a factor of proportionality), implying that (choosing the factor of proportionality to be $y_4 \neq 0$)

$$p^{j\prime} = \left(\rho', y_5^{j\prime}\right)/y_4, \qquad j = 1, ..., J, \tag{A.37}$$

$$s^{j\prime} = \left(y_3/y_4\right)\iota', \qquad j = 1, ..., J. \tag{A.38}$$

This shows that all domestic prices of the international traded goods must be equal (proportional to one another)

$$p_T^j = \rho/y_4, \qquad j = 1, ..., J,$$

the prices of the non-tradeable goods

$$p_N^j = y_5^j/y_4, \qquad j = 1, ..., J,$$

and that carbon taxes are the same across countries and across sectors within each country. For domestic prices of the international traded good to be equal, the specific tariff vectors, $\sigma^{j\prime} = y_2'/y_4$, must also be equal across countries.

To complete the proof, we next need to characterize carbon taxes. Following (A.11)—and upon using the fact that $\rho/y_4 = p_T^j$—we have that

$$y_3 = \sum_{j=1}^{J}\left(\rho, y_5^j\right)\begin{bmatrix} S_{p_T k}^j \\ S_{p_N k}^j \end{bmatrix} = \sum_{j=1}^{J}\left(\rho, y_5^j\right)' S_{pk}^j. \tag{A.39}$$

We now know that, following from the homogeneity property of S^j

$$p^{j\prime} S^j_{pk} \equiv S^j_k,$$

and so

$$\begin{aligned} y_3 &= \sum_{j=1}^{J} \left(\rho, y_5^j\right)' S^j_{pk} = y_4 \sum_{j=1}^{J} \left(p^j_T, p^j_N\right)' S^j_{pk}, \\ &= y_4 \sum_{j=1}^{J} p^{j\prime} S^j_{pk} = y_4 \sum_{j=1}^{J} \left(S^j_k\right). \end{aligned} \tag{A.40}$$

Substituting this expression for y_3/y_4 into (A.38), one obtains that

$$s^j = \left(\sum_{j=1}^{J} S^j_k\right) \iota, \tag{A.41}$$

as required.

Appendix B

Proof of Proposition 4.2:

The proof of this proposition makes use of the steps (and the equations) of the proof of Proposition 4.1. In the absence of international transfers, each country can only spend what it earns through production and net tax revenue and this constraint on national budgets complicates the outcomes of policy reforms. In terms of the model given by (4.12)-(4.15) and its differential system (4.17), the international transfers are now set to zero and left unchanged. Equation (A.12) no longer applies and so it is, therefore, no longer the case that the dual variables satisfy the condition $y_1^j = y_4,\ j = 1, ..., J$.

Accordingly, the equations $y'C = 0'$ and $y'D = 0'$ now become (since $\rho' \equiv y_1^j p_T' + (0, y_2')$),

$$\left((y_1^j p_T' + (0, y_2'), y_5^j\right), \quad y_3 \iota'\Big) \left(\begin{array}{cc} \begin{bmatrix} S^j_{p_T q} | S^j_{p_T p_N} \\ S^j_{p_N q} | S^j_{p_N p_N} \end{bmatrix} & \begin{bmatrix} S^j_{p_T s} \\ S^j_{p_N s} \end{bmatrix} \\ \left[S^j_{sq} | S^j_{sp_N}\right] & \left[S^j_{ss}\right] \end{array} \right) = (0, \ \ 0). \tag{B.1}$$

Equation (B.1) can be written as

$$\left((y_1^j p_T' + (0, y_2'), y_5^j\right), \quad y_3 \iota'\Big) \begin{pmatrix} S^j_{p\hat{p}} & S^j_{ps} \\ S^j_{s\hat{p}} & S^j_{ss} \end{pmatrix} = (0, \ \ 0)', \tag{B.2}$$

whereas (A.30) can be written as (after multiplying by y_1^j)

$$\left((y_1^j p_T' + y_1^j (0, \sigma^{j\prime}), y_1^j p_N^{j\prime}), \ \ y_1^j s^{j\prime}\right) \begin{pmatrix} S^j_{p\hat{p}} & S^j_{ps} \\ S^j_{s\hat{p}} & S^j_{ss} \end{pmatrix} = (0, \ \ 0)'. \tag{B.3}$$

Subtracting one from the other we have that

$$\left(\left(\left(y_1^j\sigma^{j\prime}-y_2^{\prime}\right),y_1^jp_N^j-y_5^j\right),\quad\left(y_1^js^{j\prime}-y_3\iota^{\prime}\right)\right)\left(\begin{array}{cc}S_{p\hat{p}}^j & S_{ps}^j\\ S_{s\hat{p}}^j & S_{ss}^j\end{array}\right)=(0,\ \ 0)^{\prime}. \tag{B.4}$$

This implies that

$$\sigma^{j\prime} = y_2^{\prime}/y_1^j, \tag{B.5}$$

$$s^{j\prime} = y_3\iota^{\prime}/y_1^j, \tag{B.6}$$

$$p_N^{j\prime} = y_5^{j\prime}/y_1^j. \tag{B.7}$$

It then follows that

$$\begin{aligned} y_3 &= \sum_{j=1}^J\left(\rho,y_5^j\right)^{\prime}S_{pk}^j=\sum_{j=1}^J y_1^j\left(p_T^j,p_N^j\right)^{\prime}S_{pk}^j,\\ &= \sum_{j=1}^J y_1^jp^{j\prime}S_{pk}^j=\sum_{j=1}^J y_1^jS_k^j. \end{aligned} \tag{B.8}$$

Substituting this expression for (B.6), $s^{j\prime}=(y_3/y_1)\,\iota^{\prime},\ j=1,...,J$ one obtains

$$s^j=\left(\sum_{i=1}^J y_1^iS_k^i\right)\iota/y_1^j. \tag{B.9}$$

as required.

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Chapter 5 Regional pollution tax coordination

5.1 Introduction

As the world becomes more integrated the linkage between international trade and the environment becomes more interesting from a policy perspective. The transboundary nature of pollution coupled with the skewed distribution of the impact[1] and origin of emissions among countries, increases the pressure on policymakers and international organizations to find solutions that mitigate the problem. Such solutions requires international coordination. But coordination—as discusses already in this thesis—is not easy to be achieved as each country is unwilling to bear the cost of environmental improvement in the fear of jeopardizing its competitive position in world markets. Instead, each country would prefer others to employ stricter environmental policies (the well known 'free riding' problem).[2]

As noted earlier in the thesis, the literature on environmental policy coordination is fairly sizeable. But it predominantly focuses on *small* open economies[3] ignoring all interesting interactions through the international good markets. Large open economies have attracted some attention—see, for example, Markusen (1975), Krutila (1991), Turunen-Red and Woodland (2004), Keen and Kotsogiannis (2012), and Kotsogiannis and Woodland (2012)—but the focus has been on either the characterization of optimal policies (either cooperative or non-cooperative) or the search of global coordinating policies.

[1] Approximately 60% of emissions produced by six countries. Twenty countries produce over 80% of global emissions (Garnaut 2008).

[2] For recent surveys on the issue see Chen and Woodland (2012) and Jones et al. (2012).

[3] See among others, Copeland (1994), Beqhin et al. (1997), Neary (2006), and Hatzipanagiotou et al (2008).

This chapter extends this literature by investigating the existence of environmental policy coordination amongst a subset of large open economies. It shows that while pollution tax coordination can potentially benefit the coordinating countries can be conducive to welfare worsening for the non-coordinating one. It also concludes that if the non-coordinating country is not passive then the welfare benefits of regional pollution tax coordination can be outweighed by a welfare increasing pollution tax reform of the non participating country. This possibility casts some doubt of the effectiveness and the welfare benefits of regional coordination.

The rest of this chapter is organized as follows. Section 5.2 briefly describes the model while Section 5.3 summarizes and concludes.

5.2 Description of the model

The model is similar to that of chapter 2 so the description will be brief. The analysis makes use of a perfectly competitive general equilibrium model of international trade, modified to take into account pollution, as by-product of production.[4] Pollution directly affects consumer welfare and does not affect the production capabilities of firms.

To simplify matters, I assume that the economy consists of three countries, indexed by the superscript $1, 2$ and 3. Each country's private sector produces N tradable commodities at a N-vector of world prices given by p. Production generates some pollutant, with the N-vector z^j denoting their level. Pollution is transboundary and given by $i'z^j$ (where i is the N-vector of 1^s and a prime indicates transposition).

[4] See, for instance, Copeland (1994), Turunen-Red and Woodland (2004) and Keen and Kotsogiannis (2012).

Global pollution is given by

$$k = \sum_{j=1}^{3} i' z^j \ . \tag{5.1}$$

Consumer's preferences are characterized by the expenditure function[5]

$$e^j(u^j, p, k) = \min_{x^j} \{p' x^j : u^j(x^j, k) \geq \tilde{u}^j\} \ , \tag{5.2}$$

which represents the minimum cost of attaining utility level u^j given international prices p and the aggregate pollution level k. Shephard's lemma implies that the compensated demand vector is given by e^j_p, while e^j_k represents the consumer's marginal willingness to pay for pollution reduction in country j. Since an increase in the level of any pollutant requires an increase in consumption to compensate the consumer for the extra pollution, expenditure is increasing in k thus $e^j_k > 0$.

Each country imposes sector-specific pollution taxes, given by the N-vector s^j. With the private sector being perfectly competitive, firms maximize their profits by choosing a feasible combination of pollution z^j and output y^j of tradable goods given technology $\tau^j(v^j)$. The production sector is therefore represented by

$$r^j(p, s^j, v^j) = \max_{y,z} \{p' y^j - s^{j\prime} z^j : (y^j, z^j) \in \tau^j(v^j)\} \ , \tag{5.3}$$

where v^j denotes the vector of endowments. The revenue function in (5.3) implies that the production sector is able to control and abate environmental discharges by altering production patterns. It has the

[5] The expenditure function is concave and linear homogeneous in prices, increasing in utility and it is assumed to be twice continuous differentiable.

standard properties: It is also a convex function, homogeneous of degree one in p and s^j and (assumed to be at least) twice continuously differentiable. Hotelling's lemma implies that the vector of (net) supply functions for tradeable commodities y^j, is given by $r_p^j(p, s^j)$.[6]

The vector of pollutants z^j (associated with the production of the N tradeable goods) is given, as an envelope property, by $-r_s^j(p, s^j)$, implying, following from equation (5.1), that

$$k = -\sum_{j=1}^{3} i' r_s^j \; . \tag{5.4}$$

Notice, for later use, that changes in global pollution level are given by

$$dk = -\sum_{j=1}^{3} i' \left(r_{ss}^j ds^j + r_{sp}^j dp \right) \; . \tag{5.5}$$

Equation (5.5) indicates that global pollution depends on the responses of each country's production sector to changes in pollution taxes and prices, given by the matrices r_{ss}^j and r_{sp}^j, respectively.

Pollution tax revenues are returned to the consumer in a lump-sum fashion. The consumer's budget constraint requires that consumers expenditure, given by $e^j(u^j, p, k)$, is equal to GDP, given by $r^j(p, s^j)$, plus any pollution tax revenues, $s^{j\prime} z^j$, collected and returned to the consumer and is therefore given by

$$e^j(u^j, p, k) = r^j(p, s^j) + s^{j\prime} z^j \; . \tag{5.6}$$

6 The endowment vectors, being fixed, is being suppressed from what follows.

Market clearing requires that

$$\sum_{j=1}^{J} \left\{ e_p^j(u^j, p, k) - r_p^j(p, s^j) \right\} = 0 \; . \tag{5.7}$$

In order to solve equation (5.7) for the world prices p, taking into account the (endogenous) determination of global pollution k, the first traded commodity has been chosen as the numeraire with its price being normalized to 1. By Walras' Law we drop the market clearing condition for that good. There are now $N-1$ market clearing conditions. Equations (5.6)-(5.7)—after making use of (5.4)—characterize the equilibrium of this economy which consists of $N+2$ variables (u^j with $j = 1, 2, 3$ and p). This implies that the system is exact and can be implicitly solved.

Perturbing now equation (5.7) one obtains[7]

$$\Lambda dp = \sum_{j=1}^{3} \left[r_{ps}^j + \left(\sum_{\nu=1}^{3} e_{pk}^{\nu} \right) i' r_{ss}^j \right] ds^j \; , \tag{5.8}$$

with

$$\Lambda \equiv \sum_{j=1}^{3} \left[e_{pp}^j - r_{pp}^j - \left(\sum_{\nu=1}^{3} e_{pk}^{v} \right) i' r_{sp}^j \right] \; , \tag{5.9}$$

being an $(N-1) \times (N-1)$. The matrix Λ is the pollution-augmented world net substitution matrix for the non-numeraire goods and is, assumed to be, of full rank and so invertible. Equation (5.8) gives the effect of policy on the international prices of the tradable goods.

In order to see how welfare is affected by the environmental policy perturb equation (5.6)—making

[7] It will be assumed that each country's income effects attach only to the numeraire good and so $e_{pu}^j = 0$. This assumption is made solely for simplicity. Relaxation of this assumption is feasible at the cost of additional notation.

use of (5.5)—to obtain

$$e_u^j du^j = \left(-m^{j\prime} - s^{j\prime} r_{sp}^j + e_k^j \sum_{j=1}^{3} i^{\prime} r_{sp}^j \right) dp - s^{j\prime} r_{ss}^j ds^j + e_k^j \sum_{j=1}^{3} i^{\prime} r_{ss}^j ds^j \ , \tag{5.10}$$

where $m^j \equiv e_p^j - r_p^j$ is the vector of imports of the non-numeraire goods.

Equation (5.10) shows that welfare is affected by prices and environmental policy distortions.

- The terms inside the parentheses in equation (5.10) consist of the terms of trade effect, given by $-m^j dp$, the impact of prices on global pollution, given by $e_k^j \sum_{j=1}^{3} i^{\prime} r_{sp}^j dp$ and the impact of prices on pollution revenues given by $-s^{j\prime} r_{sp}^j dp$.
- The second term in equation (5.10), given by $-s^j r_{ss}^j ds^j$, reflects the country's j pollution tax distortions, whereas
- The term $e_k^j \sum_{j=1}^{3} i^{\prime} r_{ss}^j ds^j$ relates to the effect of environmental policy on global pollution and so utility.

Since the focus of this chapter is on partial coordination, it will be assumed that two of the three countries (countries 1 and 2) coordinate their policies, whereas the rest (country 3) does not. The welfare consequences of environmental policy on the coordinating countries are, following form (5.10) after making use of (5.8), given by[8]

$$\sum_{j=1}^{2} e_u^j du^j = \left(-\sum_{j=1}^{2} m^{j\prime} - \sum_{j=1}^{2} s^{j\prime} r_{sp}^j + \left(\sum_{j=1}^{2} e_k^j \right) i^{\prime} \sum_{j=1}^{3} r_{sp}^j \right) \Lambda^{-1} \sum_{j=1}^{3} \left\{ \left[r_{ps}^j + \left(\sum_{\nu=1}^{3} e_{pk}^{\nu} \right) i^{\prime} r_{ss}^j \right] ds^j \right\}$$
$$+ \left(\sum_{j=1}^{2} e_k^j \right) i^{\prime} \left(\sum_{j=1}^{3} r_{ss}^j ds^j \right) - \sum_{j=1}^{2} s^{j\prime} r_{ss}^j ds^j \ , \tag{11}$$

while the welfare impact on the non-coordinating country is given by

[8] As before the existence of lump sum transfers between the coordinating countries is assumed.

$$e_u^3 du^3 = \left(-m^{3\prime} - s^{3\prime} r_{sp}^3 + e_k^3 \sum_{j=1}^{3} i' r_{sp}^j\right) \Lambda^{-1} \sum_{j=1}^{3} \left\{ \left[r_{ps}^j + \left(\sum_{\nu=1}^{3} e_{pk}^{\nu} \right) i' r_{ss}^j \right] ds^j \right\}$$
$$-s^{3\prime} r_{ss}^3 ds^3 + e_k^3 i' \left(\sum_{j=1}^{3} r_{ss}^j ds^j \right) . \quad (5.12)$$

Close inspection of equations (5.11) and (5.12) reveal that it is difficult to identify the welfare effects of pollution tax reforms. These difficulties steam from the fact that there is only available policy instrument, pollution taxes, that should be used to manipulate not only the distortions arising from the use of pollution taxes but also to correct any inefficiencies in the pattern to trade. To make progress, the analysis requires some simplifying assumptions.

Suppose that pollution and prices do not affect the compensated demands of any good other than the numeraire, that is $e_{pk}^j = 0$, $e_{pp}^j = 0$. Suppose also that (as in Chapter 2), in each country, one unit of output generates α units of pollutants. This allows us to express the amount of generated pollution as a function of the output and so $y^j = az^j$ and, since $r_p^j = y^j$ and $r_s^j = -z^j$

$$r_p^j = -ar_s^j \, , \quad (5.13)$$

this implies that

$$r_{ps}^j = -ar_{ss}^j \, . \quad (5.14)$$

where $a > 0$.[9] Equation (5.11) and (5.12) now become, respectively,

$$\sum_{j=1}^{2} e_u^j du^j = -m^{3\prime}\Phi^{-1}\sum_{j=1}^{3} r_{ss}^j ds^j + \left(\sum_{j=1}^{2} s^{j\prime} r_{sp}^j\right)\Phi^{-1}\sum_{j=1}^{3} r_{ss}^j ds^j - \sum_{j=1}^{2} s^{j\prime} r_{ss}^j ds^j \ , \tag{5.15}$$

and

$$e_u^3 du^3 = m^{3\prime}\Phi^{-1}\sum_{j=1}^{3} r_{ss}^j ds^j + s^{3\prime} r_{sp}^3 \Phi^{-1}\sum_{j=1}^{3} r_{ss}^j ds^j - s^{3\prime} r_{ss}^3 ds^3 \ , \tag{5.16}$$

where

$$\Phi = -\sum_{j=1}^{3} r_{pp}^j \ , \tag{5.17}$$

is a $(N-1)\times(N-1)$ matrix. While the global emissions level remain constant to their equilibrium level.[10]

Close inspection of equations (5.15) and (5.16) reveal that there are opposing welfare effects on the coordinating and non-participating countries. To see this more clearly, assume that none of the three countries impose pollution taxes, at the initial equilibrium, so that $s^1 = s^2 = s^3 = 0$. Then equations

[9] To the rest of the analysis for simplicity we set $\alpha = 1$.

[10] To see this substitute equation (5.8) in (5.5) and introduce the assumptions $e_{pk}^j = 0$, $e_{pp}^j = 0$ and (5.14) to obtain $dk = 0$.

(5.15) and (5.16) reduce to

$$\sum_{j=1}^{2} e_u^j du^j = -m^{3\prime}\Phi^{-1}\sum_{j=1}^{3} r_{ss}^j ds^j \ , \tag{5.18}$$

and

$$e_u^3 du^3 = m^{3\prime}\Phi^{-1}\sum_{j=1}^{3} r_{ss}^j ds^j \ . \tag{5.19}$$

which imply that

$$\sum_{j=1}^{2} e_u^j du^j = -e_u^3 du^3 \ . \tag{5.20}$$

What equation (5.20) says is that pollution tax coordination can potentially benefit the coordinating countries and can be conducive to welfare worsening for the non-coordinating one. It also suggest that if the non-coordinating country is not passive then the welfare effects of regional pollution tax coordination could be altered by a welfare increasing pollution tax reform of the non participating country.[11] This

[11] To see this, assume that the participating countries change their environmental policy proportionally to the sum of their imports/exports, that is $ds^1 = \sum_{j=1}^{2} m^j d\lambda^1$, $ds^2 = \sum_{j=1}^{2} m^j d\lambda^2$ while, the non participating country changes its pollution taxes according to $ds^3 = -m^3 d\lambda^3$,with $d\lambda^j > 0$ (and scalar). Then the welfare effects of the reforms are given by

$$\sum_{j=1}^{2} e_u^j du^j = -m^3\Phi^{-1}\sum_{j=1}^{2} r_{ss}^j m^{3\prime}\left(d\lambda^1 + d\lambda^2\right) + m^3\Phi^{-1} r_{ss}^3 m^{3\prime} d\lambda^3$$

$$e_u^3 du^3 = m^3\Phi^{-1}\sum_{j=1}^{2} r_{ss}^j m^{3\prime}\left(d\lambda^1 + d\lambda^2\right) - m^3\Phi^{-1} r_{ss}^3 m^{3\prime} d\lambda^3.$$

with r_{pp} and r_{ss} being positive semidefinite matrix.
These pollution tax reforms have opposite effect on countries welfare. The participating countries welfare increases due to the regional pollution tax coordination but decreases due to the reform followed by the non-participating country, external effect. Analogous but in opposite direction are the reforms welfare effects for the non-participating country. Consequently the overall welfare effect of the pollution tax reforms will be ambiguous depending on which dominates, the effect driven by the coordination or that driven by the pollution tax changes of the non-coordinating country.

possibility casts some doubt of the effectiveness and the welfare benefits of regional coordination.

5.3 Concluding remarks

This short chapter has investigated the welfare effects of partial pollution tax coordination. It has shown—rather surprisingly—that coordination by a subset of countries (coupled with appropriate changes in the pollution tax of the non-coordinating country) can be welfare worsening if it is welfare improving for the non-coordinating country. What this suggests is that for the benefits of tax coordination to be fully realized a global-coordination perspective is required (similar to the one taken in Chapter 1).

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