International treaties on trade and global pollution

P. Chander [1] M.A. Khan [2]

January, 1999

[1]Indian Statistical Institute, The Johns Hopkins University, and CORE.
[2]The Johns Hopkins University.

This research is part of the CLIMNEG program conducted at CORE under contract with the Belgian State, Prime Minister's Office (SSTC).

Abstract

The paper shows that global pollution need not rise under free trade in goods and/or emissions even in the complete absence of income effects. Differences in environmental concerns across the countries lead to differences in the pollution-intensity of production and thus generate the possibility of increasing world output and income without increasing the world pollution by shifting the production of the polluting good from the country with higher pollution-intensity of production to the country with lower one. We show that free trade in goods and/or emissions can induce precisely such a shifting of production with the country with greater environmental concern exporting the polluting good.

The paper also demonstrates the possibility of a first-best international treaty on global pollution in which each country or group of countries is better-off.

1 Introduction

There has been much concern and debate in recent years about the environmental consequences of free trade. Environmentalists have raised questions about the Uruguay Round of GATT/WTO on the grounds that free trade might increase global pollution, since on the one hand free trade increases the scale of economic activity and therefore of accompanying pollution and, on the other hand, it might shift the production of the pollution intensive goods from countries with strict environmental regulations towards the countries with lax ones. The response from the proponents of free trade has been the argument that environmental quality is a normal good and hence trade induced income gains would lead to stricter environmental regulations and neutralize the effect of trade liberalization on environment. The current debate thus centers around as to how strong is the income effect. In fact, recent empirical work (Grossman and Krueger (1993)) and theoretical models (Copeland and Taylor (1995) and Richelle (1996)) suggest that income gains from trade can have a substantial impact on pollution levels. This argument, though important, does not challenge but only qualifies the environmentalists claim in that it seems to concede that but for the income effects, pollution will rise under free trade.

The purpose of this paper is to show that world pollution need not rise under free trade even in the complete absence of income effects. The environmentalist's argument against free trade overlooks the fact that the much emphasized differences in the environmental concern across the countries lead to differences in the pollution-intensity of production and generate the possibility of increasing world output and income without increasing the world pollution by shifting the production of the polluting good from the country with higher pollution-intensity of production to the country with lower one. We show that free trade in goods and/or emissions can induce precisely such a shifting of production.

We begin with a model with two commodities of which one is a composite private good and the other is pollution, which is obtained as a byproduct in the production of the private good. Pollution is additive across the countries and is a pure public good (or bad) i.e. all countries are similarly exposed to a unit of pollution regardless of its source.[1] We assume that each country maximizes its utility which is linear in the private good (thus income effects are absent). We show that competitive trade in emissions or pollution permits reduces world pollution, but not necessarily the world output of the private (or polluting) good. This is because free trade in pollution permits equalizes pollution-intensity of production across the countries. Furthermore, countries with greater concern for environmental quality (North) import pollution permits and raise their pollution and output of the private good.

We then consider a model with two countries: North and South, two primary factors of production: capital and labor, and two private goods of which good

[1] See Chander and Tulkens (1992) for a formal definition of this notion in terms of what they call the transfer function.

1 is the polluting good and good 2 is the nonpolluting good. We assume that capital is mobile across the sectors, but labor is specific to the production of the nonpolluting good.The utility function of each country is assumed to be linear in good 1, so that income effects are ruled out, and log linear in good 2, so that substitution possibilities among the two goods are not ruled out. This allows us to consider pure goods trade and analyse the relationship between patterns of trade and world pollution levels. We show that if South has a "sufficiently" large endowment of the factor specific to the production of the non-polluting good, then North will export the polluting good and import the nonpolluting good. World pollution will fall below the autarky level, but the world output of the polluting good and income will rise. Welfare of North might rise and that of South might fall. We then consider trade in pollution permits along with trade in goods. We show that world pollution will fall below the autarky level whatever be the factor endowments. Furthermore, North will export the polluting good if it has a smaller endowment of the factor specific to the production of the nonpolluting good.

Free trade in emissions might reduce global pollution below the autarky level, but it would still be in excess of the first-best level as long as the countries do not determine their emissions cooperatively. We explore the possibility of such cooperation by restricting ourselves to the simple one private good model. We consider two alternative routes: a first-best treaty on global pollution preceded by (i) free trade in emissions equilibrium, and (ii) autarky equilibrium.

Chander and Tulkens (1997) show how cooperation might obtain and how the countries might negotiate a first-best treaty on global pollution. We generalize that result here in two respects: first, preferences need not be linear (also see Assumption 1' and 1" in Chander and Tulkens), and second, the initial allocation may not be the autarky equilibrium, but the free trade in emissions equilibrium. We also show that if the world output does not fall under free trade in emissions compared to the autarky equilibrium, then North can gain by establishing free trade in emissions ahead of the first-best treaty on global pollution.

The paper is organized as follows. Section 2 introduces the basic model with one private good. Section 3 introduces and characterizes the competitive emissions trading equilibrium. Section 4 introduces the model with two private goods and analyses the relationship between patterns of trade and level of global pollution. Section 5 demonstrates the possibility of an international treaty on global pollution. Section 6 draws the conclusion. All the proofs are gathered in the Appendix.

2 The Basic Model

We consider a simple model of the world economy with n countries. The countries are denoted by the index i, with $W = \{i | i = 1, 2, \cdots, n\}$ as the set of countries. There are two commodities:

(i) a composite private good, whose quantities for country i are denoted by x_i if they are consumed, and by y_i if they are produced; and

(ii) pollution, which is produced jointly with the private good and whose quantity for country i is denoted by e_i.

In fact, the pollution and the private good are related by the production functions $y_i = g_i(e_i)$, satisfying

Assumption 1 *: Each $g_i(e_i)$ is strictly concave and differentiable over an interval; and*

Assumption 2 *: There exist $e_i^0 > 0$ such that*

$$\frac{dy_i}{de_i} \equiv \gamma_i(e_i) \begin{cases} > 0 & \textit{if } 0 < e_i < e_i^0 \\ = 0 & \textit{if } e_i \geq e_i^0 \\ = \infty & \textit{if } e_i = 0. \end{cases}$$

Inputs, which are not explicitly mentioned in the production function are assumed to be fixed and subsumed in the functional symbol g_i. In particular, the production function can be written in its full form as

$$y_i = \begin{cases} e_i^{\alpha} k_i^{1-\alpha} & \text{if } e_i < ak_i \\ a^{\alpha} k_i & \text{if } e_i \geq ak_i \end{cases}$$

where k_i is the input of capital, $a > 0$ is a given constant and $\alpha \in (0, 1)$. Then, $g_i(e_i) = e_i^{\alpha}(k_i^0)^{1-\alpha}$, where k_i^0 is the fixed capital stock of country i, and $e_i^0 = ak_i^0$.[2]

Given the vector of pollution levels $(e_1, \cdots, e_n)$, a global environmental good is defined additively as

$$z = m - \sum_{i \in W} e_i,$$

where $m \geq \sum_{i \in W} e_i^0$ is a given constant.

Each country i's preferences are represented by a utility function $u_i(x_i, z)$ satisfying

Assumption 3 *: $u_i(x_i, z) = x_i + v_i(z)$ i.e. quasi-linearity, and*

Assumption 4 *: $v_i(z)$ is strictly concave, differentiable and such that*

$$\frac{dv_i}{dz} \equiv \pi_i(z) > 0 \textit{ for all } z \geq 0.$$

[2]We may think of e_i as the energy input in the production of the private good y_i and that a unit of energy use generates a unit of pollution.

We shall often refer to $\pi_i(z)$ as the *willingness to pay* of country i. Clearly, under the assumptions $\pi_i(z)$ is strictly decreasing.
Feasible states of the world economy (or allocations) are vectors $(x, e, z) \equiv (x_1, \cdots, x_n; e_1, \cdots, e_n; z)$ such that

$$\sum_{i \in W} x_i \leq \sum_{i \in W} g_i(e_i)$$

and

$$z = m - \sum_{i \in W} e_i.$$

A *Pareto efficient* state of the economy is a feasible state (x, e, z) such there exists no other feasible state (x', e', z') for which $u_i(x_i', z') \geq u_i(x_i, z)$ for all $i \in W$ with strict inequality for at least one i.

To characterize efficient states, the usual first order conditions take in this case the form of the following system of equalities:

$$\sum_{j \in W} \pi_j(z) = \gamma_i(e_i), i = 1, \cdots, n. \tag{1}$$

We shall often write $\pi_W(z)$ for $\sum_{j \in W} \pi_j(z)$ and refer to $\gamma_i(e_i)$ as the *marginal cost of abatement* of country i. Existence of Pareto efficient states follows straightforwardly from our assumptions. Moreover, in view of Assumptions 2 and 4, we have $0 < e_i < e_i^0$ for all i in any efficient state, and thus boundary problems are avoided. It is also seen that the vector of emission levels $(e_1, \cdots, e_n)$ must be the same in all Pareto efficient states - only the private good quantities might differ.

3 Games and Trade in Emissions

We consider each country i of the world economy as a player in an n-person noncooperative game. That game is defined as follows: let

$$T_i = \{(x_i, e_i) |\ 0 \leq e_i \leq e_i^0;\ 0 \leq x_i \leq g_i(e_i^0)\}, i \in W,$$

be the *strategy set* of player i. Let

$$T(S) = \{(x_i, e_i)_{i \in S} \quad | \quad 0 \leq e_i \leq e_i^0 \text{ for all } i \in S \text{ and } 0 \leq \sum_{i \in S} x_i \leq \sum_{i \in S} g_i(e_i^0)\}$$

be the *set of joint strategies* of players in S. Clearly, $T(S) \supset \times_{i \in S} T_i$. Let T denote the set of joint strategies of all players i.e. $T \equiv T(W)$.

Any joint strategy $[(x_1, e_1), \cdots, (x_n, e_n)] \in T$ induces a feasible state (x, e, z) of the economy where $z = m - \sum_{i \in W} e_i$. For each i and any $[(x_1, e_1), \cdots, (x_n, e_n)] \in T$, let $u_i(x_i, z) = x_i + v_i(z)$ with $z = m - \sum_{i \in W} e_i$ be the payoff of player i and let $u = (u_1, \cdots, u_n)$. This defines a noncooperative game $[W, T, u]$ associated with the economy.

For the noncooperative game $[W, T, u]$, the joint strategy $[(\overline{x}_1, \overline{e}_1), \cdots, (\overline{x}_n, \overline{e}_n)]$ is a Nash equilibrium if for each $i \in W$,

$$\overline{e}_i = \text{argmax}[g_i(e_i) + v_i(m - \sum_{\substack{j \in W \\ j \neq i}} \overline{e}_j - e_i)],$$

and $\overline{x}_i = g_i(\overline{e}_i)$. The first order conditions for the above maximization problems yield the system of equalities:

$$\pi_i(z) = \gamma_i(\overline{e}_i), \ i = 1, \cdots, n. \tag{2}$$

A comparison of (1) and (2) implies the familiar result that a Nash equilibrium does not induce a Pareto efficient state of the economy.

Existence and uniqueness of a Nash equilibrium for the game $[W, T, u]$ follow from standard arguments (see, e.g., Friedman (1990)). It is seen that the strategy set is compact and convex, and each player's payoff function is concave and therefore continuous and bounded.

An *autarky equilibrium* for the world economy is a feasible state $(\overline{x}_1, \cdots, \overline{x}_n; \overline{e}_1, \cdots, \overline{e}_n; \overline{z})$, with $\overline{z} = m - \sum \overline{e}_i$, induced by the Nash equilibrium $[(\overline{x}_1, \overline{e}_1), \cdots, (\overline{x}_n, \overline{e}_n)]$ of the game $[W, T, u]$.

It is assumed in a Nash or autarky equilibrium that the countries do not trade emissions, which enter both production and consumption. As seen from (2), the marginal costs of abatement are not equalized across countries which is a necessary condition or productive efficiency. We thus redefine our equilibrium concept by assuming that the countries might freely trade in emissions.[3] Trading in emissions however can be meaningful only if the countries are assigned some initial entitlements.[4] Although most of our analysis holds for any vector of initial entitlements, for the sake of a meaningful comparison we shall take these to be equal to the Nash equilibrium levels $(\overline{e}_1, \cdots, \overline{e}_n)$.

In order to introduce trade in emissions, we may think of $\overline{e}_i$ as the initial endowment of pollution permits of country i. The aggregate world supply of pollution permits is then $\sum_{i \in W} \overline{e}_i$. The aggregate world demand for pollution may be decomposed into separate demands by producers and consumers. Given

[3] It might be of interest to note that the Kyoto Protocol proposes to establish trade in emissions besides the move towards free trade in goods negotiated at the Uruguay Round of GATT/WTO.

[4] At the Kyoto Convention suggestions were also made for allocation of entitlements for emissions.

a pollution permit price $\hat{\tau}$, the aggregate world demand by producers is $\sum_{i \in W} \hat{e}_i$, where $\hat{e}_i = \text{argmax}(g_i(e_i) - \hat{\tau} e_i)$ for each i. Similarly, the aggregate world demand by consumers is $\sum_{i \in W} \hat{r}_i$, where

$$\hat{r}_i = \text{argmax}_{r_i \geq 0}[x_i - \hat{\tau} r_i + v_i(m - \sum_{j \in W} \overline{e}_j + \sum_{\substack{j \in W \\ j \neq i}} \hat{r}_j + r_i)]$$

for each i. The pollution permit price $\hat{\tau} > 0$ is an equilibrium price if $\sum_{i \in W} \hat{e}_i + \sum_{i \in W} \hat{r}_i = \sum_{i \in W} \overline{e}_i$, i.e, demand equals supply.

The net purchase of pollution permits by country i is $(\hat{e}_i + \hat{r}_i - \overline{e}_i)$ which are used by country i to increase its own pollution from $\overline{e}_i$ to $\hat{e}_i$ and to reduce world pollution by an amount $\hat{r}_i$. Country i is an exporter of pollution permits if $\hat{e}_i < \overline{e}_i$ and an importer if $\hat{r}_i > 0$. We show that given a permit price $\hat{\tau}$, a country cannot both be an exporter and an importer of pollution permits.

By definition of $\hat{e}_i$ and in view of Assumption 2, $\gamma_i(\hat{e}_i) = \hat{\tau}$ and $\hat{e}_i > 0$. By definition of $\hat{r}_i$, $\pi_i(\hat{z}) \leq \hat{\tau}$ and $(\pi_i(\hat{z}) - \hat{\tau})\hat{r}_i = 0$, where $\hat{z} = m - \sum_{i \in W} \overline{e}_i + \sum_{j \in W} \hat{r}_j$. Since by definition $\hat{r}_j \geq 0$, $\hat{z} \geq \overline{z}$. Thus, using (2), $\gamma_i(\overline{e}_i) = \pi_i(\overline{z}) \geq \pi_i(\hat{z})$. If $\hat{r}_i > 0$, $\hat{\tau} = \pi_i(\hat{z})$. Hence, $\gamma_i(\hat{e}_i) = \hat{\tau} = \pi_i(\hat{z}) \leq \pi_i(\overline{z}) = \gamma_i(\overline{e}_i)$ i.e. $\gamma_i(\hat{e}_i) \leq \gamma_i(\overline{e}_i)$. From strict concavity of g_i it follows that $\hat{e}_i \geq \overline{e}_i$. This proves that $\hat{r}_i = 0$ if $\hat{e}_i < \overline{e}_i$ and $\hat{e}_i \geq \overline{e}_i$ if $\hat{r}_i > 0$.

Gathering these ideas, we now introduce formally the concept of an emission trading equilibrium.

A *competitive emission trading equilibrium* (CETE) with respect to the Nash equilibrium $[(\overline{x}_1, \overline{e}_1), \cdots, (\overline{x}_n, \overline{e}_n)]$ is a feasible allocation $(\hat{x}_1, \cdots, \hat{x}_n; \hat{e}_1, \cdots, \hat{e}_n, \hat{z})$ such that there exists a price $\hat{\tau} > 0$ and a vector of emission reduction demands $(\hat{r}_1, \cdots, \hat{r}_n) \geq 0$ satisfying

(i) $(\hat{e}_i, \hat{r}_i) = \text{argmax}[g_i(e_i) - \hat{\tau}(e_i + r_i - \overline{e}_i) + v_i(m - \sum_{j \in W} \overline{e}_j + \sum_{\substack{j \in W \\ j \neq i}} \hat{r}_j + r_i)$

(ii) $\hat{x}_i = g_i(\hat{e}_i) - \hat{\tau}(\hat{e}_i + \hat{r}_i - \overline{e}_i)$, and

(iii) $\sum_{i \in W} \hat{e}_i + \sum_{i \in W} \hat{r}_i = \sum_{i \in W} \overline{e}_i$.

By definition, a CETE is Pareto improving compared to an autarky or Nash equilibrium. It is also seen that the vector of emission reduction demands is a noncooperative equilibrium. Existence of a CETE follows from continuity arguments. We prove uniqueness:

Suppose not. Let $(\hat{e}_1, \cdots, \hat{e}_n)$ and $(\hat{\hat{e}}_1, \cdots, \hat{\hat{e}}_n)$ be the emission levels corresponding to the two equilibria. Without loss of generality assume that $\hat{z} = m - \sum_{i \in W} \hat{e}_i \geq m - \sum_{i \in W} \hat{\hat{e}}_i = \hat{\hat{z}}$. Then we must have $\hat{e}_i < \hat{\hat{e}}_i$ for at least some i. From (i) in the definition of CETE and strict concavity of g_i it follows that $\hat{\tau} = \gamma_i(\hat{e}_i) > \gamma_i(\hat{\hat{e}}_i) = \hat{\hat{\tau}}$, where $\hat{\tau}$ and $\hat{\hat{\tau}}$ are the corresponding equilibrium permit prices. Since $\hat{z} = m - \sum_{i \in W} \overline{e}_i + \sum_{i \in W} \hat{r}_i \geq \hat{\hat{z}} > m - \sum_{i \in W} \overline{e}_i$, where $(\hat{r}_1, \cdots, \hat{r}_n)$ are the corresponding equilibrium emission reduction demands, we must have $\hat{r}_j > 0$ for at least some $j \in W$. This means that $\hat{\tau} = \pi_j(\hat{z})$ for at least some j. This leads to $\hat{\tau} = \pi_j(\hat{z}) < \pi_j(\hat{\hat{z}}) \leq \hat{\hat{\tau}}$, which contradicts the inequality $\hat{\tau} > \hat{\hat{\tau}}$ established above. Hence $(\hat{e}_1, \cdots, \hat{e}_n) = (\hat{\hat{e}}_1, \cdots, \hat{\hat{e}}_n)$. From this it is easily seen that in fact we must also have $(\hat{x}_1, \cdots, \hat{x}_n) = (\hat{\hat{x}}_1, \cdots, \hat{\hat{x}}_n)$.

In order to do a comparative analysis, we place the following stylized structure on preferences. The world economy consists of two groups of countries to be denoted by N: for north, and S: for south. Thus $N \cup S = W$ and $N \cap S = \phi$. For each $i, j \in N (i, j \in S)$ $u_i = u_j$; and $\pi_i(z) > \pi_j(z)$ for each $i \in N$ and $j \in S$.[5] Thus the willingness to pay of northern countries is higher than that of southern countries.

Proposition 1 *Compared to the autarky equilibrium, in the CETE* $(\hat{x}_1, \cdots, \hat{x}_n, \hat{e}_1, \cdots, \hat{e}_n, \hat{z})$

(i) the total world emissions are lower i.e. $\sum_{i \in W} \hat{e}_i < \sum_{i \in W} \overline{e}_i$; *the emissions of northern countries are higher i.e.* $\sum_{i \in N} \hat{e}_i > \sum_{i \in N} \overline{e}_i$ *but those of southern countries are lower i.e.* $\sum_{i \in S} \hat{e}_i < \sum_{i \in S} \overline{e}_i$;

(ii) the output per unit of emissions falls in northern countries i.e. $\hat{y}_i/\hat{e}_i < \overline{y}_i/\overline{e}_i$ *for* $i \in N$ *but it rises in the southern countries i.e.* $\hat{y}_i/\hat{e}_i > \overline{y}_i/\overline{e}_i$ *for* $i \in S$;

(iii) production of the private good shifts from the south to the north i.e. $\hat{y}_i > \overline{y}_i$ *for* $i \in N$ *and* $\hat{y}_i < \overline{y}_i$ *for* $i \in S$, *but the world output does not necessarily fall i.e.* $\sum_{i \in W} \hat{y}_i$ *is not necessarily smaller than* $\sum_{i \in W} \overline{y}_i$ *and may be even larger.*

The Proposition shows that even in the absence of income effects free trade in emissions reduces global pollution below the autarky level. Quite contrary to the environmentalists claim production shifts from the South with higher pollution-intensity of production to the North with lower one. Furthermore, the world output of the private good may not even fall.[6] We shall return to these points in greater detail below when we analyse a more general model.

4 The Model with Two Private Goods

This section extends the analysis of the previous section to the case in which the countries are endowed with two primary factors of production: labor and capital for the sake of concreteness. There are two private goods. As before

[5]Note that we are not assuming $k_i^0 = k_j^0$ for all $i, j \in N$ (or $i, j \in S$), although, since environmental quality is believed to be a normal good, it might be reasonable to assume that $k_i^0 > k_j^0$ for all $i \in N$ and $j \in S$.

[6]Observe that in the CETE the pollution levels are not coordinated across the countries and thus the CETE does not lead to a first-best allocation.

the production of good 1 requires the use of capital and generates pollution as a byproduct. This good is referred to as the "polluting good". Good 2 is produced by combining both capital and labor, and its production does not cause pollution. Thus,

$$y_{i1} = \begin{cases} e_i^{\alpha} k_{i1}^{1-\alpha} & \text{if } e_i < a k_{i1} \\ a^{\alpha} k_{i1} & \text{if } e_i \geq a k_{i1}; \end{cases}$$

$$y_{i2} = \ell_i^{\alpha} k_{i2}^{1-\alpha};$$

and

$$k_i = k_{i1} + k_{i2},\ i = 1, \cdots, n,$$

where y_{ij} is the output of good j $(= 1, 2)$ by country i, k_i is the total capital stock and ℓ_i is the labor endowment. Thus capital is a production factor which is mobile across the two sectors while labor is specific to the production of good 2.

We introduce good 2 in the utility function of each country in such a way that substitution possibilities among the two private goods are not ruled out but linearity in good 1 is maintained. Thus,

$$u_i = x_{i1} + \log x_{i2} + v_i(z),$$

where as before $z = m - \sum_{i \in W} e_i$ and x_{i1} and x_{i2} are the consumptions of good 1 and 2 by country i. We shall denote the production and consumption vectors (y_{i1}, y_{i2}) and (x_{i1}, x_{i2}), respectively, of country i by y_i and x_i.

We first describe an autarky equilibrium for this world economy. Choosing good 1 as the numeraire in all countries, let p_i denote the market clearing domestic price of good 2 in country i and let $I_i = y_{i1} + p_i y_{i2}$ denote the aggregate income. Assuming perfect competition in each country, the following equalities must be satisfied in an autarky equilibrium:

$$\begin{aligned} I_i &= y_{i1}\left(1 + \frac{k_{i2}}{k_{i1}}\right) \\ &= k_i^{1-\alpha}(e_i + p_i^{\frac{1}{\alpha}} \ell_i)^{\alpha}, \end{aligned} \tag{3}$$

by using the fact that the value of the marginal product of capital must be equal across the sectors in an equilibrium on the inputs market and that $k_{i2} = k_i - k_{i1}$. Since in an autarky equilibrium $x_{i1} = y_{i1}$, we have

$$k_i^{1-\alpha}(e_i + p_i^{1/\alpha} \ell_i)^{\alpha} - 1 = e_i k_i^{1-\alpha} / (e_i + p_i^{\frac{1}{\alpha}} \ell_i)^{1-\alpha},$$

because $x_{i1} = I_i - 1$ from utility maximization and $\alpha y_{i1} = e_i \frac{\partial I_i}{\partial e_i}$ from profit maximization by firms. This equality can be simplified and rewritten as

$$k_i^{1-\alpha} p_i^{1/\alpha} \ell_i = (e_i + p_i^{\frac{1}{\alpha}} \ell_i)^{1-\alpha}. \tag{4}$$

It would be useful to display equality (4) diagrammatically. Let $s = p_i^{1/\alpha} \ell_i$.

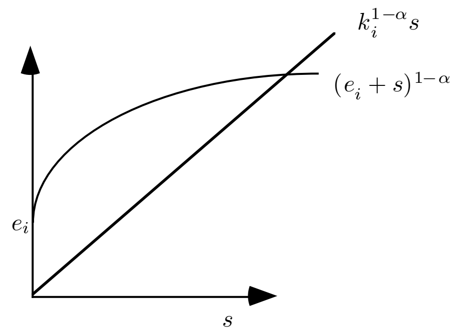

Figure 1.

The function $(e_i + s)^{1-\alpha}$ is shown to be concave in s as $0 < \alpha < 1$.

Since in an autarky equilibrium the marginal willingness to pay of each country must be equal to its marginal cost of abatement, using (3) we have

$$\pi_i(z) = \alpha k_i^{1-\alpha} / (e_i + p_i^{\frac{1}{\alpha}} \ell_i)^{1-\alpha}. \tag{5}$$

Equations (4) and (5) together imply

$$\pi_i(z) \ell_i p_i^{\frac{1}{\alpha}} = \alpha. \tag{6}$$

The equilibrium price of good 2 under autarky will be therefore smaller in the country with larger $\pi_i(z)\ell_i$.

4.1 Free trade in goods

We first consider the case in which the countries freely trade in the two goods but not in emissions. Let p be the international price of good 2 under free trade. Then equality (3) must continue to hold with p_i replaced by p. Equality (5) must also hold semilarly. Equality (4) however must change, since it is world demands and supplies and not domestic demands and supplies that must be equal. Accordingly,

$$\sum_{i \in W} \frac{k_i^{1-\alpha} p^{1/\alpha} \ell_i}{(e_i + p^{1/\alpha} \ell_i)^{1-\alpha}} = n. \tag{7}$$

In order to simplify matters we now assume that there are only two countries i.e. $n = 2$. Country 1 represents the rich North and country 2 the poor South. As before we assume that the marginal willingness to pay for the environmental quality is higher in the North i.e. $\pi_1(z) > \pi_2(z)$ for $z \geq 0$.

Proposition 2 *There exists an autarky equilibrium which is unique. If* $\pi_1(z)\ell_1 < \pi_2(z)\ell_2$, *country 1 will export the polluting good and country 2 the non-polluting good.*

Since by assumption $\pi_1(z) > \pi_2(z)$ for all z, the pollution-intensity of production is higher in country 2. Since as the proposition shows the production of the polluting good will shift from country 2 to country 1 under free trade, the world pollution must fall. The next proposition confirms that this intuition is indeed correct.

Proposition 3 *Consider a move from autarky to free trade in goods. If* $\pi_1(z)\ell_1 < \pi_2(z)\ell_2$ *for all* $z \geq 0$, *(i) world pollution will fall, but the world output of the polluting good and income will rise; (ii) output of the polluting good and pollution will rise in country 1, but fall in country 2; and (iii) country 1 might be better off and country 2 might be worse off.*

The Proposition demonstrates that global pollution need not rise under free trade in goods even in the complete absence of income effects and in fact it may fall. It may look surprising that the country with stronger environmental concerns, as measured by $\pi_i(z)$, will export the polluting good. However, this comes from the fact that differences in the environmental concerns across the countries lead to differences in the pollution-intensity of production and generate the possibility of increasing the world output without increasing the world pollution by shifting the production of the polluting good to the country with the lower pollution-intensity of production. Free trade in goods induces precisely such a shifting of production.

4.2 Free trade in emissions and goods

Notice that free trade in goods will not eliminate the gap in pollution-intensity of production, since $\pi_1(z) > \pi_2(z)$ for all z, and may not even narrow it. Free trade in goods thus does not fully exhaust the possibility of increasing the world output without increasing the world pollution. Moreover, the results above are reversed if $\pi_1(z)\ell_1 > \pi_2(z)\ell_2$. This means that free trade in goods can indeed lead to the feared "pollution havens" if the difference in the willingness to pay is sufficiently large.[7] Alternatively, South may not be sufficiently abundant in labor or the factor specific to the production of the non-polluting good. We now show that even in these cases the world pollution will fall if trade in emissions along with trade in goods is allowed as the gap in the pollution intensities of production is fully eliminated.

Proposition 4 *If $\pi_1(z)\ell_1 > \pi_2(z)\ell_2$ for all $z \geq 0$, then under free trade in goods the world pollution will rise and country 1 will export the non-polluting good and country 2 the polluting good. Suppose trade in emissions is introduced along with free trade in goods. Then the world pollution will fall but the world output of the polluting good and income will rise. Moreover, if $\ell_1 < \ell_2$, the pattern of trade will be reversed i.e. country 1 will export the polluting good and country 2 the non-polluting good and the output and pollution of country 1 will rise.*

The Proposition clarifies that the pollution-havens effect may obtain if at all not because of free trade in goods but because of lack of free trade in emissions or pollution permits. It also strengthens the conclusion of Proposition 1 as it shows that the world output and income will indeed rise if trade in emissions is allowed.

5 International Treaties and Global Pollution

Establishment of free trade in goods and pollution permits equalize marginal costs of abatement across countries, but they are still not equal to the sum of marginal willingnesses to pay, which as stated in (1) is a necessary condition for Pareto efficiency.

Is it possible for the countries to negotiate a treaty which will move the world economy from the CETE to a Pareto efficient state ? By now it is well accepted that such treaties may involve explicit international side payments (see e.g. Markusen (1975)). These side payments must naturally be such that every country or group of countries would be willing to participate in the treaty. We now explore the possibility of such a treaty. To that end we must specify the options that are available to a country or group of countries.

For the noncooperative game $[W, T, u]$, given a coalition $S \subset N$, a *coalitional equilibrium* with respect to the CETE $(\hat{x}_1, \cdots, \hat{x}_n; \hat{e}_1, \cdots, \hat{e}_n; \hat{z})$ is the joint strategy $[(\tilde{x}_1, \tilde{e}_1), \cdots, (\tilde{x}_n, \tilde{e}_n)] \in T$ such that

$$(\tilde{x}_i, \tilde{e}_i)_{i \in S} \text{ maximizes } \qquad [\sum_{i \in S}(x_i + v_i(m - \sum_{j \notin S} \tilde{e}_j - \sum_{i \in S} e_i))]$$

[7] This is of course an empirical question. Estimates using equation (2) do not suggest large differences in the willingness to pay for the *global* environmental quality (unlike the *local* environmental quality) across the countries.

$$\text{subject to} \quad \sum_{i \in S} e_i \leq \sum_{i \in S} (\hat{e}_i + \hat{r}_i); \text{and}$$
$$\sum_{i \in S} x_i \leq \sum_{i \in S} g_i(e_i) - \hat{\tau}(\sum_{i \in S} (\hat{e}_i + \hat{r}_i - \overline{e}_i));$$

and for each $j \in W \setminus S$

$$(\tilde{x}_j, \tilde{e}_j) \text{ maximizes} \quad [x_j + v_j(m - \sum_{\substack{i \neq j \\ i \in W}} \tilde{e}_i - e_j)]$$

$$\text{subject to} \quad e_i \leq \hat{e}_i + \hat{r}_i, \text{and}$$
$$x_j \leq g_j(e_j) - \hat{\tau}(\hat{e}_j + \hat{r}_j - \overline{e}_j),$$

where $\hat{\tau}$ and $(\hat{r}_1, \cdots, \hat{r}_n)$ are the pollution permit price and the pollution reduction demands corresponding to the CETE.

It is being assumed in a coalitional equilibrium that when a coalition S forms the rest of the players stay singletons. Furthermore, both coalition S and the individual players outside of S adopt their best reply strategies. It is easily seen from standard arguments that there exists a coalitional equilibrium for any $S \subset N$ and that the corresponding individual emission levels $(\tilde{e}_1, \cdots, \tilde{e}_n)$ are unique.

In the above concept of coalitional equilibrium no additional trade in pollution permits beyond that already involved in the CETE is being considered. Neither Proposition 2 nor Theorem 1 below are affected, however, if we introduce emission trading in coalitional equilibria.

Proposition 5 *For any coalition $S \subset N$, in the coalitional equilibrium*

(i) the total world emissions are not higher compared to the CETE;

(ii) the individual emission levels of the players outside of S are not lower; and

(iii) the individual emission levels of the players inside S are not higher.

Let $(\tilde{x}_1, \cdots, \tilde{x}_n; \tilde{e}_1, \cdots, \tilde{e}_n; \tilde{z})$ be the feasible allocation corresponding to the coalitional equilibrium with respect to the CETE $(\hat{x}_1, \cdots, \hat{x}_n; \hat{e}_1, \cdots, \hat{e}_n; \hat{z})$. Let v be the function defined as

$$v(S) = \sum_{i \in S} [\tilde{x}_i + v_i(\tilde{z})], S \subset W. \quad (8)$$

Let $[W, v]$ denote the n-person cooperative game with characteristic function v as defined in (8). Let $(x^*, e^*, z^*) = (x_1^*, \cdots, x_n^*; e_1^*, \cdots, e_n^*; z^*)$ be the Pareto efficient state defined as

$$x_i^* = \hat{x}_i - \frac{\pi_i^*}{\pi_W^*}(\sum_{i \in W} g_i(\hat{e}_i) - \sum_{i \in W} g_i(e_i^*)), i \in W,$$

and

$$z^* = m - \sum_{i \in W} e_i^*,$$

where $\pi_i^* = \pi_i^*(z^*)$ and $\pi_W^* = \sum_{i \in W} \pi_i^*$. (Note that $\sum \hat{x}_i = \sum_{i \in W} g_i(\hat{e}_i)$ by definition.)

Theorem 1 *The joint strategy* $[(x_1^*, e_1^*), \cdots, (x_n^*, e_n^*)]$ *belongs to the core of the game* $[W, v]$.

The theorem generalizes a result in Chander and Tulkens (1997) in two respects. First, the preferences are not assumed to be linear (also see Assumptions 1' and 1" in Chander and Tulkens). Second, the allocation (x^*, e^*, z^*) is defined from the CETE $(\hat{x}_1, \cdots, \hat{x}_n, \hat{e}_1, \cdots, \hat{e}_n; \hat{z})$ and not from the autarky equilibrium.

What might be the outcome, if no free trade in emissions is established before a first-best treaty on global pollution is negotiated ? Consider the Pareto efficient allocation

$$\overline{x}_i^* = g_i(\overline{e}_i) - \frac{\pi_i^*}{\pi_W^*}(\sum_{i \in W} g_i(\overline{e}_i) - \sum_{i \in W} g_i(e_i^*)),\ i \in W,$$

where $(\overline{x}_1, \cdots, \overline{x}_n; \overline{e}_1, \cdots, \overline{e}_n, \overline{z})$ is the autarky equilibrium. Chander and Tulkens (1997) show that under certain restrictions on preferences the above allocation belongs the core of the game in which the initial allocation is the autarky equilibrium and the players do not trade in emissions. What are the welfare implications of these two alternative paths of negotiations ? Would the northern countries be relatively worse-off if free trade in emissions is established ahead of negotiations for a first-best treaty on global pollution ? The answer is an unambiguous no if the world output of the private good under free trade in emissions rises sufficiently.

By definition,

$$\begin{aligned} x_i^* &= \hat{x}_i - \frac{\pi_i^*}{\pi_W^*}(\sum_{i \in W} g_i(\hat{e}_i) - \sum_{i \in W} g_i(e_i^*)) \\ &= \overline{x}_i^* + (g_i(\hat{e}_i) - \hat{\tau}(\hat{e}_i + \hat{r}_i - \overline{e}_i)) + \\ &\qquad + \frac{\pi_i^*}{\pi_W^*}(\sum_{i \in W} g_i(\overline{e}_i) - \sum_{i \in W} g_i(\hat{e}_i)). \end{aligned}$$

As shown earlier for each southern country i, $\hat{e}_i < \overline{e}_i$ and thus $\hat{r}_i = 0$. The first expression in parenthesis is therefore positive, since g_i is strictly concave.

The second expression in parenthesis is positive if the world output of private good falls under free trade in emissions. This means that $\sum_{i\in S} x_i^* > \sum_{i\in S} \overline{x}_i^*$, where S denotes the set of southern countries. Since $\sum_{i\in W} x_i^* = \sum_{i\in W} \overline{x}_i^*$, it follows that $\sum_{i\in N} x_i^* < \sum_{i\in N} \overline{x}_i^*$ where N is the set of northern countries. In Proposition 1 we had shown that the private good output of southern countries falls and that of northern countries rises under free trade. We conclude that if the private good output of northern countries rises sufficiently under free trade, then they would be better-off if a free trade in emissions is established ahead of negotiations for a first-best treaty on global pollution.

6 Conclusion

The main message of this paper is that it is not restrictions on free trade in goods, but lack of trade in emissions or pollution permits that can raise global pollution. As seen from Proposition 1 and 4 this result is independent of relative factor endowments.

Several assumptions limit our analysis. On the behavioral side, it is assumed that countries or governments choose their environmental policy rationally.[8] We have also assumed that the countries or governments do not use environmental regulations as a strategic trade policy. Our results will obviously be diluted, as is most often the case, if either of these behavioral assumptions does not hold.

We expect our results to change dramatically if pollution is local i.e. if the effect of pollution is confined to the country of its origin. In such a case the countries will have no interest in trading emissions. Copeland and Taylor (1994, 1997) and Khan (1996) analyse the effect of free trade on local pollution obtaining mixed results in that free trade might sometimes benefit the environmental quality and sometimes harm it depending upon the relative factor endowments and the income gap.[9] Moreover, if the effect of pollution is confined to the country of its origin, then why should it be an international problem ? The environmentalist's argument in this case does not seem to be much different from that of the traditional opponents of free trade concerned with potential job and production losses.

We have assumed labor and capital to be immobile across the countries. Beladi, Chau and Khan (1997) and Raucher (1991) study the effect of capital mobility on the environment. As seen from the proof of Proposition 4, pollution permit prices as well as prices of capital and labor will be all equalized across the

[8] Grossman and Helpman (1995) analyse the consequences of relaxing this assumption on free trade agreements.

[9] The empirical evidence in the case of local pollution is also not very clear. On the one hand, Low and Yeats (1992) show that there is some evidence that low-income countries with lax environmental regulations are developing a comparative advantage in pollution-intensive industries. On the other hand, Jaffe, Peterson, Portney and Stavins (1995) show that there is little evidence that environmental regulations have had a large impact on trade and investment patterns.

countries if either capital or labor is mobile. Thus, the message of Proposition 4 will not change if factor mobility is assumed.

Finally, we have demonstrated the possibility of a first-best treaty on global pollution following the establishment of free trade in emissions. As in Chander and Tulkens (1995, 1997) the treaty involves monetary transfers among the countries. We have also analysed the incidence of free trade in emissions on countries' welfare if the free trade in emissions is established ahead of the first-best treaty.

Appendix

Proof of Proposition 1: From the definition of CETE the following must hold:

(a) $\gamma_i(\hat{e}_i) = \gamma_j(\hat{e}_j)$ for all $i, j \in W$;
(b) $\gamma_i(\hat{e}_i) \geq \pi_i(\hat{z})$ for all $i \in W$, and
(c) $(\pi_i(\hat{z}) - \gamma_i(\hat{e}_i))\hat{r}_i = 0$,

where $(\hat{x}_1, \cdots, \hat{x}_n, \hat{e}_1, \cdots, \hat{e}_n, \hat{z})$ is the CETE allocation and $(\hat{r}_1, \cdots, \hat{r}_n)$ are the corresponding emission reduction demands.

(i) Suppose contrary to the assertion that $\sum_{i\in W} \hat{e}_i \geq \sum_{i\in W} \overline{e}_i$. Then $\pi_i(\hat{z}) \geq \pi_i(\overline{z})$ for all i. If $\hat{e}_i = \overline{e}_i \ \forall i$, then since $\gamma_i(\hat{e}_i) = \gamma_j(\hat{e}_j)$ for all i, j and using the Nash Equilibrium condition (2) it follows that

$$\pi_j(\overline{z}) = \gamma_j(\overline{e}_j) = \gamma_i(\overline{e}_i) = \pi_i(\overline{z})$$

for all $i, j \in W$. But this is a contradiction since by assumption $\pi_i(\overline{z}) < \pi_j(\overline{z})$ for $i \in S$ and $j \in N$. If $\hat{e}_i > \overline{e}_i$ for some i, then $\gamma_i(\hat{e}_i) < \gamma_i(\overline{e}_i)$ and therefore $\gamma_i(\overline{e}_i) > \gamma_i(\hat{e}_i) \geq \pi_i(\hat{z}) \geq \pi_i(\overline{z})$, which contradicts the Nash Equilibrium condition (2) i.e. $\pi_i(\overline{z}) = \gamma_i(\overline{e}_i)$. Hence we must have $\sum_{i\in W} \hat{e}_i < \sum_{i\in W} \overline{e}_i$.
Since $\sum_{i\in W} \hat{e}_i < \sum_{i\in W} \overline{e}_i$ as shown, $\hat{r}_i > 0$ for at least one i. Thus, $\pi_i(\hat{z}) = \gamma_i(\hat{e}_i)$ for at least one i. From (a) above and the fact that all countries have idential preferences in the north, it follows that $\pi_i(\hat{z}) = \gamma_i(\hat{e}_i)$ for all $i \in N$. Since $\pi_i(\hat{z}) < \pi_i(\overline{z})$ and $\pi_i(\overline{z}) = \gamma_i(\overline{e}_i)$ from (2), it follows that $\gamma_i(\hat{e}_i) < \gamma_i(\overline{e}_i)$ for all $i \in N$. Concavity of g_i implies $\hat{e}_i > \overline{e}_i$ for all $i \in N$. From $\sum_{i\in W} \hat{e}_i < \sum_{i\in W} \overline{e}_i$ and $\hat{e}_i > \overline{e}_i$ for all $i \in N$, it follows that $\sum_{i\in S} \hat{e}_i < \sum_{i\in S} \overline{e}_i$.

(ii) From $y_i = e_i^{\alpha}(k_i^0)^{1-\alpha}$, it is seen that $\hat{y}_i = \frac{1}{\alpha}\hat{e}_i\gamma_i(\hat{e}_i)$ and $\overline{y}_i = \frac{1}{\alpha}\overline{e}_i\gamma_i(\overline{e}_i)$. Since $\hat{e}_i > \overline{e}_i$ for $i \in N$ as shown, $\gamma_i(\hat{e}_i) < \gamma_i(\overline{e}_i)$. Therefore $\hat{y}_i/\hat{e}_i < \overline{y}_i/\overline{e}_i$ for $i \in N$. Conversely, it is seen that $\hat{y}_i/\hat{e}_i > \overline{y}_i/\overline{e}_i$ for $i \in S$.

(iii) Since $\hat{e}_i > \overline{e}_i$ for $i \in N$ and $\hat{e}_i < \overline{e}_i$ for $i \in S$, it is seen that $\hat{y}_i > \overline{y}_i$ for $i \in N$ and $\hat{y}_j < \overline{y}_j$ for $j \in S$. Moreover,

$$\begin{aligned} \sum_{i\in W} \hat{y}_i &= \frac{1}{\alpha}\sum_{i\in W} \hat{e}_i\gamma_i(\hat{e}_i), \text{and} \\ \sum_{i\in W} \overline{y}_i &= \frac{1}{\alpha}\sum_{i\in W} \overline{e}_i\gamma_i(\overline{e}_i), \\ \text{where } \gamma_i(\hat{e}_i) &\lesseqgtr \gamma_i(\overline{e}_i) \text{ if } \hat{e}_i \gtreqless \overline{e}_i. \end{aligned}$$

It is easy to construct examples where $\sum_{i\in W} \hat{y}_i > \sum_{i\in W} \overline{y}_i$. □

Proof of Proposition 2: Existence of an autarky equilibrium follows from exactly the same arguments as noted in Section 3. We prove uniqueness.

Suppose contrary to the assertion that there are two autarky equilibria: $(x_1, x_2; e_1, e_2; z)$ and $(x_1', x_2'; e_1', e_2'; z')$. Let (p_1, p_2) and (p_1', p_2') be the corresponding domestic prices of good 2. Without loss of generality let $z \geq z'$. If $z > z'$, then $\pi_i(z) < \pi_i(z'), i = 1, 2$. From (6) therefore $p_i > p_i', i = 1, 2$. From (4) and Figure 1, it follows that $e_i > e_i', i = 1, 2$. This contradicts the supposition that $z > z'$. Similarly, if $z = z', p_i = p_i'$ and $e_i = e_i', i = 1, 2$. Hence the autarky equilibrium is unique.

From (6) it is seen that if $\pi_1(z)\ell_1 < \pi_2(z)\ell_2$, then $p_1 > p_2$, i.e., the domestic price of good 2 is lower in country 2. Hence country 2 will export good 2. □

Proof of Proposition 3: Let $(\overline{x}; \overline{e}; \overline{z})$ be the autarky equilibrium and let $(\overline{p}_1, \overline{p}_2)$ be the corresponding domestic prices of good 2. Let $(\tilde{x}, \tilde{e}, \tilde{z})$ be the free trade in goods equilibrium and let $\tilde{p}$ be the corresponding price of good 2. Then from (5)

$$\frac{(\overline{e}_i + \overline{p}_i^{\frac{1}{\alpha}} \ell_i)^{1-\alpha}}{(\tilde{e}_i + \tilde{p}^{\frac{1}{\alpha}} \ell_i)^{1-\alpha}} = \frac{\pi_i(\tilde{z})}{\pi_i(\overline{z})}, i = 1, 2. \tag{9}$$

From (5) and (7),

$$\tilde{p}^{1/\alpha} = \frac{2\alpha}{\pi_1(\tilde{z})\ell_1 + \pi_2(\tilde{z})\ell_2}.$$

From (6),

$$\overline{p}_i^{\frac{1}{\alpha}} = \frac{\alpha}{\pi_i(\overline{z})\ell_i}, i = 1, 2.$$

Thus,

$$\left(\frac{\overline{e}_i + \dfrac{\alpha}{\pi_i(\overline{z})}}{\tilde{e}_i + \dfrac{2\alpha\ell_i}{\pi_1(\tilde{z})\ell_1 + \pi_2(\tilde{z})\ell_2}} \right)^{1-\alpha} = \left(\frac{\pi_i(\tilde{z})}{\pi_i(\overline{z})} \right)^{1-\alpha} \left(\frac{\pi_i(\tilde{z})}{\pi_i(\overline{z})} \right)^{\alpha}, i = 1, 2, \tag{10}$$

where we have substituted for $\tilde{p}^{\frac{1}{\alpha}}$ and $\overline{p}_i^{1/\alpha}$. Suppose contrary to the assertion that $\tilde{z} \leq \overline{z}$. Then, $\pi_i(\tilde{z}) \geq \pi_i(\overline{z})$ and from (10),

$$\frac{\overline{e}_i \pi_i(\overline{z})}{\pi_i(\tilde{z})} + \frac{\alpha}{\pi_i(\tilde{z})} \geq \tilde{e}_i + \frac{2\alpha\ell_i}{\pi_1(\tilde{z})\ell_1 + \pi_2(\tilde{z})\ell_2}, i = 1, 2,$$

Since $\pi_i(\tilde{z}) \geq \pi_i(\overline{z})$,

$$\overline{e}_1 + \overline{e}_2 + \frac{\alpha}{\pi_1(\tilde{z})} + \frac{\alpha}{\pi_2(\tilde{z})} \geq \tilde{e}_1 + \tilde{e}_2 + \frac{2\alpha(\ell_1 + \ell_2)}{\pi_1(\tilde{z})\ell_1 + \pi_2(\tilde{z})\ell_2}.$$

Since $\pi_1(\tilde{z})\ell_1 < \pi_2(\tilde{z})\ell_2$, the above inequalities implies $\overline{e}_1 + \overline{e}_2 > \tilde{e}_1 + \tilde{e}_2$. But this contradicts our supposition. Hence $\tilde{z} > \overline{z}$.

This proves the first part of (i). For the remaining part, since $\pi_i(\tilde{z}) < \pi_i(\overline{z})$ as shown, it is seen from (5) and (3), which must hold both in autarky and free trade equilibrium, that the world income ($= I_1 + I_2$) and therefore the world output of good 1 ($= I_1 + I_2 - 2$) must be higher under free trade in goods.

We next prove (ii). Since $\pi_i(\tilde{z}) < \pi_i(\overline{z}), i = 1, 2$, as shown, it is seen from (10) that

$$\overline{e}_i\pi_i(\overline{z}) + \alpha < \tilde{e}_i\pi_i(\tilde{z}) + \frac{2\alpha\pi_i(\tilde{z})\ell_i}{\pi_1(\tilde{z})\ell_1 + \pi_2(\tilde{z})\ell_2},\ i = 1, 2.$$

Since $\pi_1(\tilde{z})\ell_1 < \pi_2(\tilde{z})\ell_2$ and $\pi_1(\tilde{z}) < \pi_1(\overline{z})$, the above inequality implies $\overline{e}_1 < \tilde{e}_1$. Since $\overline{e}_1+\overline{e}_2 > \tilde{e}_1+\tilde{e}_2$ as shown above, $\tilde{e}_2 < \overline{e}_2$. The inequality above also implies $\overline{e}_1\pi_1(\overline{z}) < \tilde{e}_1\pi_1(\tilde{z})$, since $\pi_1(\tilde{z})\ell_1 < \pi_2(\tilde{z})\ell_2$. Therefore, $\tilde{y}_{11} > \overline{y}_{11}$, since as noted in the development of equality (4), $\alpha\overline{y}_{11} = \overline{e}_1\pi_1(\overline{z})$ and $\alpha\tilde{y}_{11} = \tilde{e}_1\pi_1(\tilde{z})$, where $\overline{y}_{11}$ and $\tilde{y}_{11}$ denote the autarky and free trade equilibrium outputs of good 1 of country 1. Since $\tilde{e}_2 < \overline{e}_2$ and $\pi_2(\tilde{z}) < \pi_2(\overline{z})$ as shown above, $\tilde{e}_2\pi_2(\tilde{z}) < \overline{e}_2\pi_2(\overline{z})$ which implies that $\tilde{y}_{21} < \overline{y}_{21}$, where $\overline{y}_{21}$ and $\tilde{y}_{21}$ denote the autarky and free trade equilibrium outputs of good 1 of country 2. Moreover, $\overline{e}_1\pi_1(\overline{z})+\overline{e}_2\pi_2(\overline{z}) < \tilde{e}_1\pi_1(\tilde{z}) + \tilde{e}_2\pi_2(\tilde{z})$ i.e. $\overline{y}_{11} + \overline{y}_{21} < \tilde{y}_{11} + \tilde{y}_{21}$.

We now prove (iii). By definition $\overline{p}_2^{1/\alpha} = \frac{\alpha}{\pi_2(\overline{z})\ell_2}$ and $\tilde{p}^{1/\alpha} = \frac{2\alpha}{\pi_1(\tilde{z})\ell_1+\pi_2(\tilde{z})\ell_2}$. Since $\pi_2(\tilde{z})\ell_2 > \pi_1(\tilde{z})\ell_1$ and $\pi_2(\tilde{z}) < \pi_2(\overline{z})$, it follows that $\tilde{p} > \overline{p}_2$. From utility maximization $\tilde{x}_{22} = 1/\tilde{p}$ and $\overline{x}_{22} = 1/\overline{p}_2$. Hence $\tilde{x}_{22} < \overline{x}_{22}$. Since $\pi_i(\tilde{z}) < \pi_i(\overline{z})$, inequalities (9) and (3), which must hold also under free trade, together imply that

$$\tilde{I}_2 = k_2^{1-\alpha}(\tilde{e}_2 + \tilde{p}^{1/\alpha}\ell_2)^\alpha > k_2^{1-\alpha}(\overline{e}_2 + \overline{p}_2^{1/\alpha}\ell_2)^\alpha = \overline{I}_2.$$

Therefore, from utility maximization $\tilde{x}_{21} = \tilde{I}_2 - 1 > \overline{x}_{21} = \overline{I}_2 - 1$. The incidence of free trade on the welfare of country 2 is ambiguous, since $\tilde{x}_{22} < \overline{x}_{22}$ but $\tilde{x}_{21} > \overline{x}_{21}$. We therefore construct a special case in which country 2 is worse off and country 1 is better off. In this special case

$$u_i(x_i, z) = x_{i1} + \log x_{i2} + \overline{\pi}_i z, i = 1, 2,$$

where $\overline{\pi}_i > 0$ fixed is the marginal willingness to pay of country i. Keeping all other assumptions the same, it is easy to see that

$$\tilde{x}_{11} = \overline{x}_{11}, \tilde{x}_{21} = \overline{x}_{21},$$

but

$$\tilde{x}_{12} = \frac{1}{\tilde{p}} > \frac{1}{\overline{p}_1} = \overline{x}_{12}$$

and

$$\tilde{x}_{22} = \frac{1}{\tilde{p}} < \frac{1}{\overline{p}_2} = \overline{x}_{22}.$$

Hence country 2 is worse off, but country 1 is better off.

This completes the proof of Proposition 3. □

Proof of Proposition 4: The proof of the first part is along the same lines as in Proposition 3 and hence it is avoided. We prove the remaining.

Let $(\hat{x}, \hat{e}, \hat{z})$ be the free trade in emissions and goods equilibrium and let $\hat{p}$ be the corresponding price of good 2. Then as in Proposition 1 it is seen that the following inequality must be satisfied.

$$\pi_1(\hat{z}) = \frac{\alpha k_1^{1-\alpha}}{(\hat{e}_1 + \hat{p}^{1/\alpha}\ell_1)^{1-\alpha}} = \frac{\alpha k_2^{1-\alpha}}{(\hat{e}_2 + \hat{p}^{1/\alpha}\ell_2)^{1-\alpha}} > \pi_2(\hat{z}). \tag{11}$$

From (7) it follows that

$$\hat{p}^{1/\alpha} = \frac{2\alpha}{\pi_1(\hat{z})(\ell_1 + \ell_2)}.$$

From (5), which must also hold under free trade in emissions and goods we have

$$\begin{aligned} \left(\frac{\overline{e}_1 + \dfrac{\alpha}{\pi_1(\overline{z})}}{\hat{e}_1 + \dfrac{2\alpha\ell_1}{\pi_1(\hat{z})(\ell_1 + \ell_2)}} \right)^{1-\alpha} &= \frac{\pi_1(\hat{z})}{\pi_1(\overline{z})}, \\ \text{and} \qquad \left(\frac{\overline{e}_2 + \dfrac{\alpha}{\pi_2(\overline{z})}}{\hat{e}_2 + \dfrac{2\alpha\ell_2}{\pi_1(\hat{z})(\ell_1 + \ell_2)}} \right)^{1-\alpha} &= \frac{\pi_1(\hat{z})}{\pi_2(\overline{z})}, \end{aligned} \tag{12}$$

Suppose contrary to the assertion that $\hat{e}_1 + \hat{e}_2 > \overline{e}_1 + \overline{e}_2$. Then $\pi_1(\hat{z}) > \pi_1(\overline{z}) > \pi_2(\overline{z})$ and (12) imply

$$\overline{e}_1\pi_1(\overline{z}) + \overline{e}_2\pi_2(\overline{z}) > \hat{e}_1\pi_1(\hat{z}) + \hat{e}_2\pi_1(\hat{z}).$$

But this contradicts our supposition that $\overline{e}_1 + \overline{e}_2 \leq \hat{e}_1 + \hat{e}_2$. Hence as is easily seen

$$\overline{e}_1 + \overline{e}_2 > \hat{e}_1 + \hat{e}_2$$

and

$$\overline{e}_1\pi_1(\overline{z}) + \overline{e}_2\pi_2(\overline{z}) < \hat{e}_1\pi_1(\hat{z}) + \hat{e}_2\pi_1(\hat{z}),$$

that is

$$\overline{y}_{11} + \overline{y}_{21} < \hat{y}_{11} + \hat{y}_{21}.$$

This proves that world pollution is lower but the world output of the polluting good and therefore income is higher. It is also seen from (12) that if $\ell_1 < \ell_2$, then $\overline{e}_1\pi_1(\overline{z}) < \hat{e}_1\pi_1(\hat{z})$ i.e. the output of the polluting good of country 1 is higher.

The proof of this Proposition is completed by showing that if $\ell_1 < \ell_2$, then country 2 will export the non-polluting good. In view of (3), let

$$\hat{I}_i = k_i^{1-\alpha}(\hat{e}_i + \hat{p}^{1/\alpha}\ell_i)^\alpha.$$

Then

$$\frac{\partial \hat{I}_i}{\partial \ell_i} = \frac{\alpha k_i^{1-\alpha}\hat{p}^{1/\alpha}}{(\hat{e}_i + \hat{p}^{1/\alpha}\ell_i)^{1-\alpha}},$$

and

$$\frac{\partial \hat{I}}{\partial k_i} = \frac{(1-\alpha)(\hat{e}_i + \hat{p}^{1/\alpha}\ell_i)^\alpha}{k_i^\alpha},$$

Using (11), it follows that the factor prices and therefore factor intensities of production are equalized across the countries under free trade in emissions and goods. Since $\ell_2 > \ell_1$ and the factor intensities of production are equal, $\hat{y}_{22} > \hat{y}_{12}$. However, from utility maximization $\hat{x}_{22} = \hat{x}_{12} = \frac{1}{\hat{p}}$ and $\hat{x}_{22} + \hat{x}_{12} = \hat{y}_{22} + \hat{y}_{12}$. This proves that country 2 must export good 2. □

Proof of Proposition 5:

(i) By definition of the coalition equilibrium the first-order conditions imply

$$\begin{aligned} \sum_{j\in S} \pi_j(\tilde{z}) &\le \gamma_i(\tilde{e}_i), i \in S, \\ \gamma_i(\tilde{e}_i) &= \gamma_j(\tilde{e}_j) \text{ for } i,j \in S, \\ \text{and} \quad \pi_i(\tilde{z}) &\le \gamma_i(\tilde{e}_i), i \in W \setminus S. \end{aligned} \tag{13}$$

Suppose contrary to the assertion that total world emissions are higher, i.e., $\sum_{i\in W}\tilde{e}_i > \sum_{i\in W}\hat{e}_i$. Then

$$\pi_i(\tilde{z}) > \pi_i(\hat{z}) \text{ for all } i \in W.$$

As for emissions of S are concerned two cases arise: (a) $\sum_{j\in S}\pi_j(\tilde{z}) > \gamma_i(\hat{e}_i)$ for each $i \in S$, in which case $\gamma_i(\tilde{e}_i) > \gamma_i(\hat{e}_i)$ from (13) and thus $\hat{e}_i > \tilde{e}_i$ for all $i \in S$; and (b) $\sum_{j\in S}\pi_j(\tilde{z}) \leq \gamma_i(\hat{e}_i)$ for each $i \in S$, which means $\pi_i(\hat{z}) < \gamma_i(\hat{e}_i)$ and thus $\hat{r}_i = 0$ and therefore $\tilde{e}_i = \hat{e}_i$ for all $i \in S$. This means that $\sum_{i\in S}\tilde{e}_i \leq \sum_{i\in S}\hat{e}_i$ in either case.

For emission levels of players outside of S, if $\pi_j(\hat{z}) < \gamma_j(\hat{e}_j)$, then $\hat{r}_j = 0$ and thus $\tilde{e}_j \leq \hat{e}_j$. If $\pi_j(\hat{z}) \geq \gamma_j(\hat{e}_j)$, then $\pi_j(\tilde{z}) > \gamma_j(\hat{e}_j)$ and thus $\tilde{e}_j < \hat{e}_j$. Therefore, $\tilde{e}_j \leq \hat{e}_j$ for all $j \in W \setminus S$.

Hence we have shown that $\sum_{i\in W}\tilde{e}_i \leq \sum_{i\in W}\overline{e}_i$. But this is a contradiction to our supposition. Hence (i).

(ii) Since $\sum_{i\in W}\tilde{e}_i \leq \sum_{i\in W}\hat{e}_i$ as shown, $\pi_i(\tilde{z}) \leq \pi_i(\hat{z})$ for all i. For $i \in W \setminus S, \pi_j(\hat{z}) \leq \gamma_i(\hat{e}_j)$ implies $\pi_j(\tilde{z}) \leq \gamma_j(\hat{e}_j)$. This means that $\tilde{e}_j = \hat{e}_j$ if $r_j = 0$ and $\tilde{e}_j \geq \hat{e}_j$ if $r_j > 0$. Hence $\tilde{e}_j \geq \hat{e}_j$ for $j \in W \setminus S$.

(iii) From (i) and (ii) $\sum_{i\in S}\tilde{e}_i \leq \sum_{i\in S}\hat{e}_i$. From (13) and the fact that $\gamma_i(\hat{e}_i) = \gamma_j(\hat{e}_j)$ for all $i, j \in S$, it follows that $\tilde{e}_i \leq \hat{e}_i$ for all $i \in S$. This completes the proof:

□

Proof of Theorem 1: Suppose contrary to the assertion that $[(x_1^*, e_1^*), \cdots, (x_n^*, e_n^*)]$ is not in the core of the game $[W, v]$. Then there exists a coalition $S \subset W, S \neq W$ and the corresponding coalitional equilibrium $[(\tilde{x}_1, \tilde{e}_1), \cdots, (\tilde{x}_n, \tilde{e}_n)]$ such that

$$\sum_{i\in S}(\tilde{x}_i + v_i(\tilde{z})) > \sum_{i\in S}(x_i^* + v_i(z^*)) \tag{14}$$

where $\tilde{z} = m - \sum_{i\in W}\tilde{e}_i$.

Let $(\tilde{x}_1^*, \cdots, \tilde{x}_n^*; e_1^*, \cdots, e_n^*; z^*)$ be the Pareto efficient allocation defined as follows:

$$\tilde{x}_i^* \;=\; \tilde{x}_i - \frac{\pi_i^*}{\pi_W^*}(\sum_{i\in W} g_i(\tilde{e}_i) - \sum_{i\in W} g_i(e_i^*)), i \in W,$$

and $z^* = m - \sum_{i\in W} e_i^*$. It is easily seen that $\sum_{i\in W}\tilde{x}_i^* = \sum_{i\in W} x_i^*$. We show that (14) leads to the contradiction that $\sum_{i\in W}\tilde{x}_i^* > \sum_{i\in W} x_i^*$.
First,

$$\begin{aligned}
\sum_{i\in S}\tilde{x}_i^* &= \sum_{i\in S}\tilde{x}_i - (\sum_{i\in S}\frac{\pi_i^*}{\pi_W^*})(\sum_{j\in W} g_j(\tilde{e}_j) - \sum_{j\in W} g_j(e_j^*)) \\
&\geq \sum_{i\in S}\tilde{x}_i - (\sum_{i\in S}\frac{\pi_i^*}{\pi_W^*})(\pi_W^*(\sum_{j\in W}\tilde{e}_j - \sum_{j\in W} e_j^*)) \\
&\qquad \text{(from concavity of } g_i \text{ and Pareto efficiency condition (1))} \\
&\geq \sum_{i\in S}\tilde{x}_i - \sum_{i\in S}\pi_i^*(z^* - \tilde{z}) \\
&\geq \sum_{i\in S}\tilde{x}_i - \sum_{i\in S}(v_i(z^*) - v_i(\tilde{z})),
\end{aligned}$$

since from concavity $v_i(z^*) - v_i(\tilde{z}) \geq \pi_i^*(z^* - \tilde{z})$ for all i.
Thus,

$$\begin{aligned}
\sum_{i\in S}(\tilde{x}_i^* + v_i(z^*)) \geq & \sum_{i\in S}(\tilde{x}_i + v_i(\tilde{z}) \\
> & \sum_{i\in S}(x_i^* + v_i(z^*)).
\end{aligned}$$

Hence $\sum_{i\in S}\tilde{x}_i^* > \sum_{i\in S} x_i^*$. Thus we only need to show that $\sum_{i\in W\setminus S}\tilde{x}_i^* \geq \sum_{i\in W\setminus S} x_i^*$.
By definition

$$\begin{aligned}
\sum_{i\in W\setminus S}\tilde{x}_i^* &= \sum_{i\in W\setminus S}\tilde{x}_i - (\sum_{i\in W\setminus S}\frac{\pi_i^*}{\pi_W^*})(\sum_{i\in W}\tilde{x}_i - \sum_{i\in W} x_i^*) \\
&= \sum_{i\in W\setminus S} x_i^* + (\sum_{i\in W\setminus S}\tilde{x}_i - \sum_{i\in W\setminus S}\hat{x}_i) - (\sum_{i\in W\setminus S}\frac{\pi_i^*}{\pi_W^*})(\sum_{i\in W}\tilde{x}_i - \sum_{i\in W}\hat{x}_i) \\
&= \sum_{i\in W\setminus S} x_i^* + (1 - \sum_{i\in W\setminus S}\frac{\pi_i^*}{\pi_W^*})(\sum_{i\in W\setminus S}(\tilde{x}_i - \hat{x}_i)) \\
&\quad + \sum_{i\in W\setminus S}(\frac{\pi_i^*}{\pi_W^*})(\sum_S \hat{x}_i - \sum_S \tilde{x}_i).
\end{aligned}$$

From Proposition 5, the last two terms are both nonnegative. Hence the theorem. □

References

[1] Beladi, H., N.H. Chau and M.A. Khan (1997), "North-South investment flows and strategic environmental policies," mimeo, The Johns Hopkins University.

[2] Chander, P. and H. Tulkens (1992), "Theoretical foundations of negotiations and cost sharing in transfrontier pollution problems," *European Economic Review,* 36(2/3), 288-299.

[3] Chander, P. and H. Tulkens (1995), "A core-theoretical solution for the design of cooperative agreements on transfrontier pollution," *International Tax and Public Finance,* 2(2), 279-294.

[4] Chander, P. and H. Tulkens (1997), "The core of an economy with multilateral environmental externalities," *International Journal of Game Theory,* 26, 379-401.

[5] Copeland, B.R. and M.S. Taylor (1994), "North-South trade and the environment," *Quarterly Journal of Economics,* 109, 755-787.

[6] Copeland, B.R. and M.S. Taylor (1995), "Trade and transboundary pollution," *American Economic Review,* 85, 716-737.

[7] Copeland, B.R. and M.S. Taylor (1997), "A simple model of trade, capital mobility, and the environment," NBER Working Paper 5898.

[8] Friedman, J. (1990), "Game theory with applications to economics, second edition," Oxford University Press.

[9] Grossman, G. and A. Krueger (1993), "Environmental impacts of a North American free trade agreement," in Peter Garber (ed.), *The Mexico-US Free Trade Agreemnent.* Cambridge, Mass.: MIT Press.

[10] Grossman, G. and E. Helpman (1995), "The politics of free trade agreements," *American Economic Review,* 85, 667-690.

[11] Jaffe, A., S. Peterson, P. Portney and R. Stavins (1995), "Environmental regulation and the competitiveness of U.S. manufacturing: What does the evidence tell us," *Journal of Economic Literature,* XXXIII, 132-163.

[12] Khan, M.A. (1996), "Free trade and the environment," *The Journal of International Trade and Economic Development,* 113-136.

[13] Low, P. and A. Yeats (1992), "Do 'dirty' industries migrate?" in Patrick Low (ed.), *International Trade and the Environment: World Bank Discussion Paper,* (Washington, DC: World Bank).

[14] Markusen, J.R. (1975), "Cooperative control of international pollution and common property resources," *Quarterly Journal of Economics,* 89(3), 618-632.

[15] Rauscher, M. (1991), "National environmental policies and the effects of economic integration," *European Journal of Political Economy,* 7, 313-329.

[16] Richelle, Y. (1996), "Trade incidence on transboundary pollution: Free trade can benefit the global environmental quality," University of Laval Discussion Paper no 9616.