Environmental Benefits from International Trade*

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Short abstract: We analyze the impact of international trade with transboundary pollution and *endogenous-environmental policy* on welfare and emissions in a general equilibrium model. Pollution in one industry affects another industry's output domestically and abroad.
With international trade in final goods emission levels and emission-permit prices are the same regardless of whether emission rights are tradable or not. Even without internationally tradable-emission rights countries account for foreign marginal damages from emissions. In autarchy, environmental policy does not account for all marginal damages. Still, sometimes a country's consumer may be better off in autarchy even if she received all emission-permit revenues under trade.

Long abstract: We analyze the impact of international trade with transboundary pollution and *endogenous-environmental policy* on welfare and emissions in a general equilibrium model. Pollution in one industry affects the output of another industry domestically and abroad. With international trade in final goods we first analyze a centralized framework with internationally tradable-emission permits where environmental policy satisfies Pareto optimality. Second, a decentralized scenario where countries choose the environmental policy that maximizes domestic welfare. We compare the trade cases with autarchy.
With international trade in final goods *i)* emission levels and emission-permit prices of the decentralized and centralized frameworks are equal and *ii)* the decentralized formulation takes into account also foreign marginal damages from emissions. Despite that environmental policy with international trade accounts for all the marginal damages from emissions, and in autarchy does not, we find that in some instances under free international trade-even if the entire emission-permit revenues are passed to a single country's representative consumer-this consumer may be better off in autarchy than in trade.

Key words: Pollution, International Trade, Autarchy, Optimal environmental policy.

JEL Classification: F10, Q20

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1. Introduction

This paper analyses the impact of international trade with trans-boundary pollution and endogenous environmental policy on welfare and on the level of global emissions. To a large extent the literature of international trade and *endogenous* environmental policy focuses on the case when pollution externalities affect consumers' utility (see Siebert et al., 1980, Copeland and Taylor 1994, 2004, and Hoel, 2005). However, the effects of international trade on environmental quality and welfare when pollution externalities affect industrial output have largely been neglected. We focus on the case where pollution directly influences production, but does not directly affect consumers' utility. Pollution is emitted by some industries which affects the output of other industries (domestically and abroad). One can think of carbon emissions in the production of steel affecting the output of agriculture or fisheries, because of more droughts, in the domestic economy and foreign countries. We investigate the case when the pollution's origin is irrelevant for the scale of environmental damage, that is, the effect of pollution on production is the same regardless of its place of origin. When international trade in final goods is allowed we analyze two scenarios regarding emission policy. First, a centralized framework with internationally-tradable emission permits where a social planner (we can think of it as the United Nations) chooses the level of emissions that is consistent with Pareto optimality. Second, a decentralized scenario where each country chooses the level of emissions that maximizes domestic welfare. Since our objective is to analyze the impact of international trade on welfare and emissions we compare the trade cases with the case of autarchy—without international trade neither in goods nor in emission permits and where each country sets environmental policy as to maximize domestic welfare.

There are three basic findings. First, with international trade in final goods emission levels and emission-permit prices of the decentralized and centralized frameworks are equal. Thus, in the decentralized framework prices of emission permits are equal across countries even in the absence of international trade in permits. That is, in the decentralized framework, as long as there is international trade in final goods, the individual countries' environmental policy always takes into account all marginal damages from emissions. Second, if there is free trade in final goods, and in addition emission permits' revenue collection is distributed to consumers as lump-sum transfers and this distribution occurs in the same manner in the centralized and decentralized formulations, then each formulation leads to the same competitive equilibrium.

Third, we compare the trade and autarchy scenarios. In some instances under free international trade —even if the entire emissions' revenue collection is passed to a single country's representative consumer— this consumer may be better off in autarchy than in trade. This occurs despite the fact that environmental policy with international trade accounts for all the marginal damages from emissions, whereas environmental policy in autarchy does not. This may occur when the production of a country is largely susceptible to emissions. A low vulnerable country in autarchy will set a loose environmental policy allowing for a relatively high amount of emissions, thus, boosting the production of emitting goods. The effects of this policy on the highly vulnerable country will be to choose a tight environmental policy, thus, boosting sectors that are sensitive to emissions in the low vulnerable country. If the low vulnerable region now chooses an international trade regime a tighter environmental policy is set in place. It is possible that the costs of this tighter policy are sufficiently large so that even if all emission permits revenues are transferred to this country the region would be better off in autarchy than in trade.

There are several contributions to the literature. First, the paper analyses the effect of international trade when pollution externalities affect industrial output, whereas the literature usually assumes that externalities affect consumers' utility. Second, the international trade literature focusing on the effects of pollution on production does not explore the issue of optimal emission policy (Benarroch and Thille, 2001 and Copeland and Taylor, 1999), as we do. There are two papers closer to our model. Manne and Stephan (2005) consider international trade models where climate change affects production. They focus on a cooperative framework with optimal emissions and show that optimal emissions are independent of emission revenues distribution and compensation[1]. Manne and Stephan, however, leave unexplored the welfare and environmental implications of trade. Copeland and Taylor (1997) develop a small open economy model with local pollution where environmental capital is negatively affected by emissions over time. However, emission levels are not optimally set since emission policy in their model ignores the long-run effects of pollution.

Third, we develop a model that accounts for different regional and sectoral effects of pollution which are well documented by the fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) Work Group II (2007). For example, carbon emissions inducing a small increase in mean temperature may lead to an increase in agricultural production on higher latitudes, but since regions near the equator are more prone to droughts pollution may lead to a decrease of agricultural output in these areas. Besides spatial differences, sectoral vulnerabilities also exist.

[1] This work is related to the work of Baumol (1972) who considers the closed economy case.

Fisheries, farms and tourism are more sensitive to changes in environmental conditions (IPCC, 2007) whereas heavy industries and many forms of energy production are less dependent on them. Costs and benefits from pollution are, therefore, not equally distributed across economic sectors and world regions.

The framework presented is a two-goods two-countries world-economy model. One of the goods produced is vulnerable to pollution, but does not pollute. The other sector pollutes, but is not vulnerable to pollution. We can think of agriculture as the affected or vulnerable-non-polluting sector and the heavy industry as the non-vulnerable-emitting sector. The world economy consists of two countries, the North and the South. Across countries the vulnerable sector's production is differently affected by emissions. Each country is endowed with capital and labor whose endowment may differ across countries. Pollution affects the vulnerable sector of both countries regardless of the provenance of emissions. We abstract from within country income distributional effects and assume that in each country there is a representative consumer who derives satisfaction from consuming the two final goods produced. Consumers' preferences are identical across countries and pollution does not affect consumers' preferences.

In section two, we present the model with international trade in both final goods and emission permits, where a social planner chooses the level of emissions that is consistent with Pareto optimality. Section three describes the case with international trade in final goods but not in emission permits, where each government independently chooses the level of emissions that maximizes domestic welfare. Section four describes the autarchy scenario. Section five compares the welfare and pollution effects of international trade. Section six concludes.

2. The model: International trade in goods and permits and centralized emission policy

We assume a world economy consisting of two countries, the North and the South[2]. Two internationally traded goods are produced, good A and good E. In each country there is a representative consumer. Consumers across countries have identical preferences, and derive satisfaction from consuming goods A and E. In the South the representative consumer is endowed with $\bar{K}$ and $\bar{L}$ units of capital and labor, respectively. We presume that there is no international capital nor labor mo-

[2] Our qualitative results do not change assuming that the world economy consists of two regions each composed of more than one country.

bility. We use an asterisk to denote the North quantities and prices. Thus, $\bar{K}^*$ and $\bar{L}^*$, respectively, denote the capital and labor endowments in the North. The production of commodity E causes a pollution discharge which negatively affects the production of good A. Good E could be thought as electricity from greenhouse-gas-emitting coal burning power stations and good A could be thought as agriculture which is sensitive to changes in climate and precipitation. Pollution generated in a country does not only affect domestic production, but also the other country's production of good A. Capital and labor are employed in the production of good A and E. The production of good E employs environmental services in addition. Environmental services, among others, include the natural degradation of waste and the elimination and long-term storage of carbon dioxide from the atmosphere through the use of natural carbon sinks. We presume that the demand of environmental services equals the pollution emitted by sector E in each country. In the absence of environmental policy environmental services constitute a common pool problem. We concentrate on the case of optimal environmental policy where a (world wide acting) social planner chooses emission levels that are consistent with Pareto optimality. For each unit of emissions a permit is issued which allows firms in sector E to generate one emission unit. Emission permits are sold internationally and the price of an emission permit is determined by the market. Revenues from emission permits are passed to representative consumers of the South and North as lump sump transfers.

2.1. Firms

In the South the output of good A and E are, respectively, denoted as Y_A and Y_E. In the following, subscripts A and E denote good A and good E. Emissions from producing good E in each country instantaneously negatively affect the output of sector A in both countries.

The emitting sector E use the following production techniques in the South and North, correspondingly,

$$Y_E = \left(K_E^{\varepsilon} L_E^{1-\varepsilon}\right)^{\beta} s^{1-\beta} \tag{1}$$

and

$$Y_E^* = \left(\left(K_E^*\right)^{\varepsilon} \left(L_E^*\right)^{1-\varepsilon}\right)^{\beta} \left(s^*\right)^{1-\beta}, \tag{2}$$

where $0 \leq \beta \leq 1$ and $0 \leq \varepsilon \leq 1$. K_E, L_E and s denote the capital, labor and environmental services employed in the production of good E in the South, similarly, K_E^*, L_E^* and s^* are those for the

North. We assume that the environmental services employed equal the pollution emitted by sector E in each country[3]. Let d and d^* denote the amount of emission discharge of sector E, respectively, in the South and North. Setting the amount of emissions equal to the demand of environmental services, $d = s$ and $d^* = s^*$; (1) and (2) can be rewritten as

$$Y_E = G(K_E, L_E, d) = \left(K_E^{\varepsilon} L_E^{1-\varepsilon}\right)^{\beta} d^{1-\beta} \tag{3}$$

and

$$Y_E^* = G(K_E^*, L_E^*, d^*) = \left((K_E^*)^{\varepsilon} (L_E^*)^{1-\varepsilon}\right)^{\beta} (d^*)^{1-\beta}. \tag{4}$$

The pollution generated in the North and South decreases the output of sector A by means of a pollution externality. Similar to Benarroch and Thille (2001) we assume the following production functions

$$Y_A = F(K_A, L_A; D) = (1 - \eta D) K_A^{\alpha} L_A^{1-\alpha} \tag{5}$$

and

$$Y_A^* = F^*(K_A^*, L_A^*; D) = (1 - \eta^* D)(K_A^*)^{\alpha} (L_A^*)^{1-\alpha} \tag{6}$$

where $0 \leq \alpha \leq 1$. K_A and L_A denote the capital and labor services employed in the production of output Y_A in the South. K_A^* and L_A^*, similarly, denote those for the North. Production of good A is negatively affected by global emissions $D \equiv d + d^*$. The regional vulnerability to pollution of commodity-A's production are captured by the constants η, $\eta^* > 0$ (in equations (5) and (6)).

While the supply of environmental services is large, these services are not supplied in infinite amounts to the degree by which environmental degradation takes place. We include a capacity constraint $\bar{D}$ on aggregate emission levels as follows

$$d + d^* \leq \bar{D}. \tag{7}$$

We also assume that η and η^* are sufficiently large such that if aggregate emissions equal $\bar{D}$ the output of good A in either country equals zero. That is,

[3] While there are different approaches relating output and emissions (see for example Dasgupta and Heal 1979 pp.78-91, Copeland and Taylor, 1994), we follow the approach followed by Dasgupta and Mäler (2000) where emissions equal the demand of environmental services.

$$\frac{1}{\bar{D}} \leqq \eta \qquad \text{and} \qquad \frac{1}{\bar{D}} \leqq \eta^* \tag{8}$$

holds.

Let r, w and τ denote the rental rate of capital, labor wage rate and the price of an emission permit allowing a firm to generate one unit of pollution, respectively, in the South. Let p_A and p_E denote the prices of goods A and E in the South. Taking the externality D and prices as given sector A in the South maximizes profits $(p_A F(K_A, L_A; D) - rK_A - wL_A)$ and as long as sector A is open it maximizes profits by setting the value of the marginal physical product of capital and labor equal to factor prices. The first order condition associated with profit maximization in sector A are given by

$$p_A \frac{\partial F(K_A, L_A; D)}{\partial K_A} \leq r, \quad \text{if } K_A > 0 \quad \text{then} \quad p_A \frac{\partial F(K_A, L_A; D)}{\partial K_A} = r, \tag{9}$$

$$p_A \frac{\partial F(K_A, L_A; D)}{\partial L_A} \leq w, \quad \text{if } L_A > 0 \quad \text{then} \quad p_A \frac{\partial F(K_A, L_A; D)}{\partial L_A} = w. \tag{10}$$

Thus, if sector A in the South is open (9) and (10) will hold with equality.

Similarly, taking prices as given sector E in the South chooses the amount of capital, labor and emissions that maximize profits $(p_E G(K_E, L_E, d) - rK_A - wL_A - \tau d)$. The first order conditions associated with sector E's optimization problem equal

$$p_E \frac{\partial G(K_E, L_E, d)}{\partial K_E} \leq r, \tag{11}$$

$$p_E \frac{\partial G(K_E, L_E, d)}{\partial L_E} \leq w, \tag{12}$$

$$p_E \frac{\partial G(K_E, L_E, d)}{\partial d} \leq \tau. \tag{13}$$

If sector E in the South is open then $(11) - (13)$ will hold with equality. Let r^*, w^* and τ^* denote the rental rate of capital, labor wage rate and the price of an emission permit in the North. Let p_A^* and p_E^* denote the prices of goods A and E in the North. Sectors A and E in the North solve a similar optimization problem to that of the South and similar expressions as (9)-(13) also hold for the North (where all variables have an asterisk superscript).

2.2. Consumers

The preferences of the representative consumer in the South and North are given by

$$U(c_A, c_E) = c_A^{\gamma} c_E^{1-\gamma}, \tag{14}$$

and

$$U(c_A^*, c_E^*) = (c_A^*)^{\gamma} (c_E^*)^{1-\gamma} \tag{15}$$

with $0 < \gamma < 1$. c_A and c_E (c_A^* and c_E^*) denote consumption of goods A and E in the South (in the North), respectively. The representative consumer of the South owns capital $\bar{K}$ and labor $\bar{L}$ which are inelastically supplied to domestic firms at prices r and w. The representative consumer in the South chooses non-negative values of c_A and c_E to solve

$$\max\left\{c_A^{\gamma} c_E^{1-\gamma} \left| p_A c_A + p_E c_E \leq w\bar{L} + r\bar{K} + T\right.\right\} \tag{16}$$

where T is a lump-sum transfer from permit-sale revenues .

Similarly, the representative consumer in the North chooses non-negative values of c_A^* and c_E^* to solve

$$\max\left\{(c_A^*)^{\gamma} (c_E^*)^{1-\gamma} \left| p_A^* c_A^* + p_E^* c_E^* \leq w^* \bar{L}^* + r^* \bar{K}^* + T^*\right.\right\} \tag{17}$$

where T^* is also a lump-sum transfer. T and T^* are more precisely defined in the next sections.

2.3. Centralized environmental policy with internationally-tradable permits.

In this section we consider the case where in the presence of international trade in goods a social planner aims at choosing the global level of emissions that is consistent with Pareto optimality. We call this setting the centralized scenario. Pareto optimality requires the utility maximization of any arbitrarily chosen representative consumer subject to the requirement that the other country's representative consumer is not worse off, and also subject to the conditions that final goods world supplies equals world demands (see Baumol (1972) for a similar formulation in the one country case). In addition, subject to the feasibility conditions that aggregate labor and capital used in each country equal their per-country supplies, and subject to the constraint that the bound on global emissions is satisfied.

For each unit of emissions the social planner issues an emission permit that allows firms to emit one unit of pollution. The social planner sells permits at price τ, determined by the market. Emission permits revenue collection is passed to the representative consumers of the South and North. More precisely, the social planner solves

$$\max U\left(c_A, c_E\right) \tag{18}$$

s.t.

$$U\left(c_A^*, c_E^*\right) \geqq g^* \tag{19}$$

$$c_A + c_A^* \leqq (1-\eta D)\left(K_A^\alpha L_A^{1-\alpha}\right) + (1-\eta^* D)\left(K_A^*\right)^\alpha \left(L_A^*\right)^{1-\alpha} \tag{20}$$

$$c_E + c_E^* \leqq \left(K_E^\varepsilon L_E^{1-\varepsilon}\right)^\beta d^{1-\beta} + \left(\left(K_E^*\right)^\varepsilon \left(L_E^*\right)^{(1-\varepsilon)}\right)^\beta \left(d^*\right)^{1-\beta} \tag{21}$$

$$d + d^* = D, \tag{22}$$

$$L_A + L_E \leqq \bar{L}, \qquad L_A^* + L_E^* \leqq \bar{L}^* \tag{23}$$

$$K_A + K_E \leqq \bar{K}, \qquad K_A^* + K_E^* \leqq \bar{K}^* \tag{24}$$

$$D \leq \bar{D}, \tag{25}$$

where g^* is a positive constant, (20) and (21) are feasibility constraints in final goods, (22) defines aggregate emissions, (23) and (24) are labor and capital feasibility constraints and (25) is the capacity constraint on global emissions.

2.4. Equilibrium

Definition.- A competitive equilibrium for the centralized scenario with international trade in emission permits and final goods are quantities

$$\hat{x} = \left(\hat{c}_A, \hat{c}_E, \hat{c}_A^*, \hat{c}_E^*, \hat{Y}_A, \hat{K}_A, \hat{L}_A, \hat{Y}_E, \hat{K}_E, \hat{L}_E, \hat{d}, \hat{Y}_A^*, \hat{K}_A^*, \hat{L}_A^*, \hat{Y}_E^*, \hat{K}_E^*, \hat{L}_E^*, \hat{d}^*, \hat{D}\right)$$

prices, $\hat{r}$, $\hat{w}$, $\hat{r}^*$, $\hat{w}^*$, and $\hat{\tau}$, price ratio $\frac{\hat{p}_A}{\hat{p}_E}$ and transfers $\hat{T}$ and $\hat{T}^*$ such that

i) Given prices and transfers, $(\hat{c}_A,\ \hat{c}_E)$ and $(\hat{c}_A^*,\ \hat{c}_E^*)$ solve the optimization problem of the respective consumer in the South and North.

ii) Given prices, $\left(\hat{Y}_A,\ \hat{K}_A,\ \hat{L}_A\right)$, and $(\hat{Y}_A^*,\ \hat{K}_A^*,\ \hat{L}_A^*)$ solve the profit maximization problem of sector A in the South and North, respectively.

iii) Given prices, $(\hat{Y}_E,\ \hat{K}_E,\ \hat{L}_E,\ \hat{d})$ and $(\hat{Y}_E^*,\ \hat{K}_E^*,\ \hat{L}_E^*,\ \hat{d}^*)$ solve the profit maximization problem of sector E in the South and North, respectively.

iv) $\hat{x}$ solves the social planner's optimization problem (18).

v) The capacity constraint on global emissions $\left(\hat{D} \leq \bar{D}\right)$ is satisfied.

vi) Market clearing conditions:

- in final goods hold, that is equations (20) and (21) are satisfied.

- in factors of production in each country hold, that is equations (23) and (24) are satisfied

-in emissions (22) holds; and

vii) The social planner collects revenues from emission permits and passes them to consumers as lump-sum transfers. That is,

$$\hat{T} + \hat{T}^* = \hat{\tau} D. \tag{26}$$

2.5. Solution

Since long the economic literature (see Baumol and Bradford, 1972) has shown that non-convex production possibility sets exist when externalities are present. Similar to Baumol and Bradford and Benarroch and Thille, we find that in some instances the production possibility set of our economy is non-convex. The problems associated with this phenomenon, in particular the determination of the optimal allocation of resources is described in more detail in Baumol and Bradford. They demonstrate that as long as the source of non-convexities is only due to externalities there exists a Pigouvian tax that can sustain a competitive economy that is technologically efficient. However, they also point out that "Pigouvian taxes cannot change the shapes of the technological relationships in the economy, and hence cannot remove the problems of evaluation of efficiency which non-convexity introduces". In our model the constraint qualification for using Kuhn-Tucker conditions for optimality is satisfied[4]. Moreover, since the objective function associated with the social planner's problem is concave the Kuhn-Tucker conditions associated with problem (18) are sufficient for a global maximum.

[4] The Jacobian matrix of the binding constrait of problem (18) has full rank.

We now solve the social planner's problem (18) by means of Kuhn-Tucker conditions. The Lagrangian associated with problem (18) is given by

$$\begin{aligned}\mathcal{L} \;=\;& U\left(c_A, c_E\right) + \lambda\left(U\left(c_A^*, c_E^*\right) - g^*\right) \\ & + v_A\left(\left(1-\eta D\right)\left(K_A^{\alpha} L_A^{1-\alpha}\right) + \left(1-\eta^* D\right)\left(K_A^*\right)^{\alpha}\left(L_A^*\right)^{1-\alpha} - c_A - c_A^*\right) \\ & + v_E\left(\left(K_E^{\varepsilon} L_E^{1-\varepsilon}\right)^{\beta} d^{1-\beta} + \left(\left(K_E^*\right)^{\varepsilon}\left(L_E^*\right)^{1-\varepsilon}\right)^{\beta}\left(d^*\right)^{1-\beta} - c_E - c_E^*\right) \\ & + \pi\left(D - d - d^*\right) \\ & + \theta_K\left(\bar{K} - K_A - K_E\right) + \theta_L\left(\bar{L} - L_A - L_E\right) \\ & + \theta_K^*\left(\bar{K}^* - K_A^* - K_E^*\right) + \theta_L^*\left(\bar{L}^* - L_A^* - L_E^*\right)\end{aligned} \tag{27}$$

where λ, v_A, v_E, π, θ_K, θ_L, θ_K^* and θ_L^* are Lagrange multipliers. By assumption, η (the parameter that controls for the vulnerability of sector A to emissions) is sufficiently large such that if $D = \bar{D}$ then the output of sector A in each country is zero. This ensures that $D < \bar{D}$. Therefore, we do not include a multiplier for the constraint $D \leq \bar{D}$. Optimality with regard to c_A, c_E, c_A^*, and c_E^* implies

$$\frac{U_{c_A}\left(\hat{c}_A, \hat{c}_E\right)}{U_{c_E}\left(\hat{c}_A, \hat{c}_E\right)} = \frac{U_{c_A^*}\left(\hat{c}_A^*, \hat{c}_E^*\right)}{U_{c_E^*}\left(\hat{c}_A^*, \hat{c}_E^*\right)} = \frac{\hat{v}_A}{\hat{v}_E} \tag{28}$$

where $U_{c_j}\left(\hat{c}_A, \hat{c}_E\right)$ for $i = A, E$ denotes the partial derivative of $U\left(c_A, c_E\right)$ with respect to c_j evaluated at the equilibrium solution. Let $\widehat{MB}$ denote the marginal benefits from emissions in the South and $\widehat{MB}^*$ denote the marginal benefits from emissions in the North. Optimality requires

$$\mathcal{L}_d \leq 0 \Rightarrow \widehat{MB} \equiv \hat{v}_E\left(1-\beta\right)\left(\frac{\hat{K}_E^{\varepsilon}\hat{L}_E^{1-\varepsilon}}{\hat{d}}\right)^{\beta} \leq \hat{\pi} \tag{29}$$

$$\mathcal{L}_{d^*} \leq 0 \Rightarrow \widehat{MB}^* \equiv \hat{v}_E\left(1-\beta\right)\left(\frac{\left(\hat{K}_E^*\right)^{\varepsilon}\left(\hat{L}_E^*\right)^{1-\varepsilon}}{\hat{d}^*}\right)^{\beta} \leq \hat{\pi} \tag{30}$$

If $\hat{d}$ and $\hat{d}$ are positive then (29) and (30), respectively, hold with equality. Let $\widehat{MD}$ denote the marginal damages from emissions

$$\mathcal{L}_D \leq 0 \Rightarrow \hat{\pi} \leq \hat{v}_A \left(\eta \hat{K}_A^{\alpha} \hat{L}_A^{1-\alpha} + \eta^* \left(\hat{K}_A^* \right)^{\alpha} \left(\hat{L}_A^* \right)^{1-\alpha} \right) = \widehat{MD} \tag{31}$$

Equations (29) $-$ (31) indicate that if the marginal damages from emissions $\widehat{MD}$ are greater than their per-country marginal benefits $\widehat{MB}$ and $\widehat{MB}^*$ then it is optimal to set emissions at the country level equal to zero. Since emissions must be positive in at least one country else the aggregate output of good E would equal zero and utility would be minimal, D must be positive and (31) holds with equality. As it is well known, optimal environmental policy with internationally-tradable permits must account for all the marginal damages from emissions as indicated in equation (31).

If production of good E takes place in both countries, then, using (29)-(31) we obtain that marginal benefits from emissions equal marginal damages from emissions in both countries, that is,

$$\widehat{MB} = \hat{v}_A \left(\eta \hat{K}_A^{\alpha} \hat{L}_A^{1-\alpha} + \eta^* \left(\hat{K}_A^* \right)^{\alpha} \left(\hat{L}_A^* \right)^{1-\alpha} \right) = \widehat{MB}^* \tag{32}$$

Since at the country level damages from emissions are equal regardless of their source of origin marginal benefits from emissions in each country are equalized across countries as indicated in equation (32). Solving for d from (32), emissions at the country level are given by

$$\hat{d} = \left(\frac{\hat{v}_E}{\hat{v}_A} \frac{1-\beta}{\eta \hat{K}_A^{\alpha} \hat{L}_A^{1-\alpha} + \eta^* \left(\hat{K}_A^* \right)^{\alpha} \left(\hat{L}_A^* \right)^{1-\alpha}} \right)^{\frac{1}{\beta}} \hat{K}_E^{\varepsilon} \hat{L}_E^{(1-\varepsilon)} \tag{33}$$

$$\hat{d}^* = \left(\frac{\hat{v}_E}{\hat{v}_A} \frac{1-\beta}{\eta \hat{K}_A^{\alpha} \hat{L}_A^{1-\alpha} + \eta^* \left(\hat{K}_A^* \right)^{\alpha} \left(\hat{L}_A^* \right)^{1-\alpha}} \right)^{\frac{1}{\beta}} \left(\hat{K}_E^* \right)^{\varepsilon} \left(\hat{L}_E^* \right)^{1-\varepsilon} \tag{34}$$

and aggregate emission equals

$$\hat{D} = \left(\frac{\hat{v}_E}{\hat{v}_A} \frac{1-\beta}{\eta \hat{K}_A^{\alpha} \hat{L}_A^{1-\alpha} + \eta^* \left(\hat{K}_A^* \right)^{\alpha} \left(\hat{L}_A^* \right)^{1-\alpha}} \right)^{\frac{1}{\beta}} \left(\hat{K}_E^{\varepsilon} \hat{L}_E^{(1-\varepsilon)} + \left(K_E^* \right)^{\varepsilon} \left(L_E^* \right)^{1-\varepsilon} \right) \tag{35}$$

The allocation of capital and labor across sectors is given by

$$\frac{\alpha \hat{v}_A \left(1 - \eta \hat{D} \right) \hat{K}_A^{\alpha} \hat{L}_A^{1-\alpha}}{\hat{K}_A} \leq \theta_K, \tag{36}$$

$$\frac{(1-\alpha) \hat{v}_A \left(1 - \eta \hat{D} \right) \hat{K}_A^{\alpha} \hat{L}_A^{1-\alpha}}{\hat{L}_A} \leq \theta_L, \tag{37}$$

$$\frac{\beta\varepsilon\hat{v}_E\left(\hat{K}_E^{\varepsilon}\hat{L}_E^{1-\varepsilon}\right)^{\beta}\hat{d}^{1-\beta}}{\hat{K}_E} \leq \theta_K, \tag{38}$$

$$\frac{\beta\left(1-\varepsilon\right)\hat{v}_E\left(\hat{K}_E^{\varepsilon}\hat{L}_E^{1-\varepsilon}\right)^{\beta}\hat{d}^{1-\beta}}{\hat{L}_E} \leq \hat{\theta}_L, \tag{39}$$

similarly for Northern quantities.

A competitive equilibrium for this economy is found using equations $(20)-(25)$ and $(28)-(39)$, and setting $\frac{\hat{p}_A}{\hat{p}_E} = \frac{\hat{p}_A^*}{\hat{p}_E^*} = \frac{\hat{v}_A}{\hat{v}_E}$, $\hat{r} = \theta_K$, $\hat{w} = \theta_L$, $r^* = \theta_K^*$, $w^* = \theta_L^*$, $\tau = \tau^* = \pi$.

Notice that in the absence of transportations costs and barriers to trade, prices of final goods are equal across countries. Moreover, since emissions permits are internationally traded their price is also equal across countries.

3. Decentralized environmental policy without internationally-tradable permits.

In this section we describe a scenario in which each country's government chooses the domestic level of emission that maximizes domestic welfare. We called this setting the decentralized scenario. While in the previous section a (world) social planner chooses world-wide environmental policy, now each country's government chooses the nation's environmental policy that maximizes domestic welfare. While we allow for international trade in final goods, international trade in permits is not possible now. We can think of this scenario as the case where countries do not reach an agreement on cooperation relating environmental policy, and governmental authorities do not recognize emission permits from other countries. Still there is international trade in final goods and domestic environmental policy.

More precisely, the government of the South takes emissions from the North as given and solves

$$\max U\left(c_A, c_E\right) \tag{40}$$

s.t.

$$c_A + c_A^* = \left(1 - \eta\left(d + d^*\right)\right)\left(K_A^{\alpha} L_A^{1-\alpha}\right) + \left(1 - \eta^*\left(d + d^*\right)\right)\left(K_A^*\right)^{\alpha}\left(L_A^*\right)^{1-\alpha} \tag{41}$$

$$c_E + c_E^* = \left(K_E^{\varepsilon} L_E^{(1-\varepsilon)}\right)^{\beta} d^{1-\beta} + \left(\left(K_E^*\right)^{\varepsilon}\left(L_E^*\right)^{(1-\varepsilon)}\right)^{\beta}\left(d^*\right)^{1-\beta} \tag{42}$$

$$L_A + L_E = \bar{L}, \qquad K_A + K_E = \bar{K}, \tag{43}$$

$$D \leq \bar{D}, \tag{44}$$

The difference between the decentralized and the centralized scenarios is that under the decentralized scenario the government in the South does not ensure that the presentative consumer of the North is not worse off and vice versa. However, the government in the South recognizes that there is international trade in final goods. A similar optimization problem also applies for the government of the North.

Definition.- A competitive equilibrium for the decentralized solution, without international trade in emission permits are quantities

$$\underset{\sim}{x} = (\underset{\sim}{c}_A, \underset{\sim}{c}_E, \underset{\sim}{Y}_A, \underset{\sim}{K}_A, \underset{\sim}{L}_A, \underset{\sim}{Y}_E,\ \underset{\sim}{K}_E,\ \underset{\sim}{L}_E, \underset{\sim}{d})$$

and,

$$\underset{\sim}{x}^* = (\underset{\sim}{c}_A^*, \underset{\sim}{c}_E^*, \underset{\sim}{Y}_A^*,\ \underset{\sim}{K}_A^*,\ \underset{\sim}{L}_A^*,\ \underset{\sim}{Y}_E^*,\ \underset{\sim}{K}_E^*,\ \underset{\sim}{L}_E^*,\ \underset{\sim}{d}^*)$$

prices, $\underset{\sim}{r}$, $\underset{\sim}{w}$, $\underset{\sim}{\tau}$, $\underset{\sim}{r}^*$, $\underset{\sim}{w}^*$, and $\underset{\sim}{\tau}^*$, price ratios $\frac{\underset{\sim}{p}_A}{\underset{\sim}{p}_E}$ and $\frac{\underset{\sim}{p}_A^*}{\underset{\sim}{p}_E^*}$ and transfers $\underset{\sim}{T}$ and $\underset{\sim}{T}^*$ such that

i) Given prices and transfers, $(\underset{\sim}{c}_A, \underset{\sim}{c}_E)$ and $(\underset{\sim}{c}_A^*, \underset{\sim}{c}_E^*)$ solve the optimization problem of the respective consumer in the South and North.

ii) Given prices, $(\underset{\sim}{Y}_A, \underset{\sim}{K}_A, \underset{\sim}{L}_A)$, and $(\underset{\sim}{Y}_A^*,\ \underset{\sim}{K}_A^*,\ \underset{\sim}{L}_A^*)$ solve the profit maximization problem of sector A in the South and North, respectively.

iii) Given prices, $(\underset{\sim}{Y}_E,\ \underset{\sim}{K}_E,\ \underset{\sim}{L}_E, \underset{\sim}{d})$ and $(\underset{\sim}{Y}_E^*,\ \underset{\sim}{K}_E^*,\ \underset{\sim}{L}_E^*,\ \underset{\sim}{d}^*)$ solve the profit maximization problem of sector E in the South and North, respectively.

iv) $\underset{\sim}{x}$ solves the optimization problem of the government in the South.

v) $\underline{x}^*$ solves the optimization problem of the government in the North.

vi) The capacity constraint on global emissions $\left(\underline{D} \leq \bar{D}\right)$ is satisfied.

vii) Market clearing conditions:

- in final goods hold, that is, equations (20) and (21) are satisfied.

- in factors of production in each country hold, that is, equations (23) and (24) are satisfied and

viii) Transfers equal emission-permits revenue collection

$$\underline{T}+\underline{T}^* = \underline{\tau}\,\underline{d}+\underline{\tau}^*\,\underline{d}^* \tag{45}$$

Proposition 1. *In economies with international trade in final goods the centralized solution* ***with international-tradable permits*** *and the decentralized solution* ***without internationally-tradable permits*** *lead to the same level of emissions and is independent of emission revenues distribution.*

Proof. See appendix■

Thus, not only in the centralized framework optimal emissions are chosen so that their marginal benefit equal all marginal damages. This result holds in the decentralized framework as well with international trade in goods domestic emissions are chosen so that their marginal domestic benefit equals world marginal damages. The explanation for this result is that pollution affects production of good A domestically and abroad which directly affects its international supply and price. If the marginal damages from pollution in the North $p_A\eta^*\left(K_A^*\right)^{\alpha}\left(L_A^*\right)^{1-\alpha}$ were relatively small when compared to the South $p_A\eta\left(K_A^{\alpha}L_A^{1-\alpha}\right)$ and optimal emission only accounted for marginal domestic damages then emissions would be set at a relative high level in the North. Thus, the marginal effect of pollution in the South will be larger than in the North. With this the production of good A in the South will decline more than that in the North putting additional pressure in the international price of good A. Thus, even under the decentralized framework, optimal environmental policy must account for damages caused internationally.

Proposition 2. *In the decentralized solution* ***without-internationally tradable permits****, if sector E is open in both countries, emission permit's prices are equal across countries.*

Proof. See proof of proposition 1 in the Appendix■

The reason for this is that the marginal damage of one unit of emissions is equal regardless of whether emissions originate in the South or North. Since domestic environmental policy accounts for *all* marginal damages from emission and the price of an emission permit in each country equals the value of marginal damages (domestic and foreign) then prices of emission permits must be equal across countries.

Notice that if the damages from emissions were also dependent on the origin of emissions then the proposition may not hold true.

Proposition 3. *Emission-permits prices in the centralized solution with tradable permits and the decentralized solution without tradable permits are identical.*

Proof. See proof of proposition 1 in the Appendix■

Proposition 4. *In economies with international trade in final goods the centralized solution and the decentralized solution lead to the same relative prices of final goods* $\left(\frac{p_A}{p_E}\right)$.

Proof. See proof of proposition 1 in the Appendix■

Proposition 5. *With international trade in final goods, if transfers redistribution takes place in the same manner under the centralized and the decentralized settings (*$\hat{T}=\underline{T}$ *and* $\hat{T}^{*}=\underline{T}^{*}$*), then the competitive equilibrium of the centralized and the decentralized formulations are identical.*

Proof. Since relative prices of final goods as well as emissions are equal under either setting, the equilibrium labor wage rates and rental rates of capital are equal in the two scenarios. Thus, if transfers are distributed in the same manner under the centralized and decentralized settings the proposition holds.■

Corollary. If externalities are of the type studied here, where they only directly affect production but do not enter into the consumers' utility functions and there is international trade in all final goods the centralized and decentralized solutions (where countries independently and selfishly choose emission's policy) are equal. The importance of this result is that as long as there is free international trade in final goods (international trade in permits is not necessary) and emissions are set optimally by individual countries, the solution is the same as the one of a centralized emission policy. Thus, no agreement is necessary among countries. That is, a central authority or an international agreement on environmental policy is not compulsory if there is undistorted trade at least in the pollution affected sector. A further integration of the commodity markets and further international trade agreements are desirable for mitigating environmental problems.

Regarding factor prices, as long as technologies across countries differ (in particular, $\eta \neq \eta^*$) factor price equalization may not occur. However, if specialization does not take place in either country and technologies across countries are identical ($\eta \neq \eta^*$) then the Heckscher-Ohlin (Heckscher, 1950, Ohlin, 1933 and Samuelson, 1949) tendency for factor price equalization takes place.

4. Autarchy

In the autarchy setting the only connection between the two economies is the externality that sector E causes in the other country's sector A.

In the absence of international trade in goods and emission permits, the government of the South sets the domestic consumption of goods A and E equal to domestic production and chooses consumption levels c_A^{NT}, c_E^{NT} and emissions d^{NT} that maximize domestic welfare as follows,

$$\max U(c_A^{NT}, c_E^{NT}) \tag{46}$$

s.t.

$$c_A^{NT} = \left(1 - \eta\left(d + d^{NT*}\right)\right)\left(K_A^{NT}\right)^{\alpha}\left(L_A^{NT}\right)^{1-\alpha}, \tag{47}$$

$$c_E^{NT} = \left(\left(K_E^{NT}\right)^{\varepsilon}\left(L_E^{NT}\right)^{1-\varepsilon}\right)^{\beta}\left(d^{NT}\right)^{1-\beta} \tag{48}$$

We now use the superscript NT to denote the autarchic prices and quantities. In the case of a country in the North the superscript NT is followed by an asterisk.

The first order conditions of problem (46) equal

$$\frac{U_{c_A^{NT}}\left(c_A^{NT}, \hat{c}_E^{NT}\right)}{U_{c_E^{NT}}\left(c_A^{NT}, c_E^{NT}\right)} = \frac{v_A^{NT}}{v_E^{NT}} \tag{49}$$

and

$$v_A^{NT}\eta\left(K_A^{NT}\right)^{\alpha}\left(L_A^{NT}\right)^{1-\alpha} = v_E^{NT}\left(1-\beta\right)\left(\frac{\left(K_E^{NT}\right)^{\varepsilon}\left(L_E^{NT}\right)^{1-\varepsilon}}{d^{NT}}\right)^{\beta} \tag{50}$$

where $\hat{v}_A^{NT}$, $\hat{v}_E^{NT}$ are Lagrange multipliers associated with constraints (47) and (48), respectively.

For the North we have

$$\frac{U_{c_A^{NT*}}\left(c_A^{NT*},c_E^{NT*}\right)}{U_{c_E^{NT*}}\left(c_A^{NT*},c_E^{NT*}\right)}=\frac{v_A^{NT*}}{v_E^{NT*}} \tag{51}$$

and

$$v_A^{NT*}\eta^*\left(K_A^{NT*}\right)^{\alpha}\left(L_A^{NT*}\right)^{1-\alpha}=v_E^{NT*}\left(1-\beta\right)\left(\frac{\left(K_E^{NT*}\right)^{\varepsilon}\left(L_E^{NT*}\right)^{1-\varepsilon}}{d^{NT*}}\right)^{\beta} \tag{52}$$

where v_A^{NT*}, and v_E^{NT*} are Lagrange multipliers similar to the ones specified for the South. In autarchy all of the first order conditions hold with equality since sector A and E must be open in both countries.

From the optimization problem of the consumers it follows that $\frac{v_A^{NT}}{v_E^{NT}}=\frac{U_{c_A^{NT}}\left(c_A^{NT},c_E^{NT}\right)}{U_{c_E^{NT}}\left(c_A^{NT},c_E^{NT}\right)}=\frac{p_A^{NT}}{p_E^{NT}}$ and $\frac{v_A^{NT*}}{v_E^{NT*}}=\frac{U_{c_A^{NT*}}\left(c_A^{NT*},c_E^{NT*}\right)}{U_{c_E^{NT*}}\left(c_A^{NT*},c_E^{NT*}\right)}=\frac{p_A^{NT*}}{p_E^{NT*}}$. Using these two expressions and equations (50) and (52), optimality in sector E implies

$$\hat{p}_A^{NT}\eta\left(K_A^{NT}\right)^{\alpha}\left(L_A^{NT}\right)^{1-\alpha} = \hat{p}_E^{NT}\left(1-\beta\right)\left(\frac{\left(K_E^{NT}\right)^{\varepsilon}\left(L_E^{NT}\right)^{1-\varepsilon}}{d^{NT}}\right)^{\beta}=\hat{\tau}^{NT} \tag{53}$$

$$\hat{p}_A^{NT*}\eta^*\left(K_A^{NT*}\right)^{\alpha}\left(L_A^{NT*}\right)^{1-\alpha} = \hat{p}_E^{NT*}\left(1-\beta\right)\left(\frac{\left(K_E^{NT*}\right)^{\varepsilon}\left(L_E^{NT*}\right)^{1-\varepsilon}}{d^{NT*}}\right)^{\beta}=\hat{\tau}^{NT*} \tag{54}$$

Equation (50) and (52) indicate that in contrast to the international trade scenarios, in autarchy only domestic marginal damages from emissions are accounted for while foreign marginal damages are ignored. Damages to sector A in the foreign country are irrelevant for the decision of the optimizing policy maker because there are no economic relations between the two countries and higher damages to the affected sector abroad have no influence on the consumption and utility of the domestic country.

5. Simplified model on welfare and emission levels under trade and autarchy

To obtain additional insight regarding welfare and emission levels under trade and autarchy we solve a simplified model analytically by assuming that $\varepsilon=1$ and $\alpha=0$ such that,

$$Y_E=K_E^{\beta}d^{1-\beta}, \qquad Y_E^*=\left(K_E^*\right)^{\beta}\left(d^*\right)^{1-\beta} \tag{55}$$

and

$$Y_A=\left(1-\eta D\right)L_A, \qquad Y_A^*=\left(1-\eta^*D\right)\left(L_A^*\right) \tag{56}$$

5.1. Trade equilibrium solution

Using the international market clearing condition of good E the relative price of final goods $\frac{\hat{p}_E}{\hat{p}_A}$ is given by

$$\frac{\hat{p}_E}{\hat{p}_A}=\frac{1}{1-\beta}\left(\frac{\sigma}{\gamma+\sigma}\right)^{\beta}\left(\frac{\bar{L}+\bar{L}^*}{\eta\bar{L}+\eta^*\bar{L}^*}\right)^{\beta}\left(\frac{\eta\bar{L}+\eta^*\bar{L}^*}{\left(\bar{K}+\bar{K}^*\right)^{\beta}}\right) \tag{57}$$

where $\sigma=(1-\beta)(1-\gamma)$. Substituting (57) into (33) – (34) pollution levels per country are given by

$$\hat{d} = \left(\frac{\hat{p}_E}{\hat{p}_A}\frac{1-\beta}{\eta\bar{L}+\eta^*\bar{L}^*}\right)^{\frac{1}{\beta}}\bar{K}=\left(\frac{\sigma}{\gamma+\sigma}\right)\left(\frac{\bar{L}+\bar{L}^*}{\eta\bar{L}+\eta^*\bar{L}^*}\right)\left(\frac{\bar{K}}{\bar{K}+\bar{K}^*}\right) \tag{58}$$

$$\hat{d}^* = \left(\frac{\hat{p}_E}{\hat{p}_A}\frac{1-\beta}{\eta\bar{L}+\eta^*\bar{L}^*}\right)^{\frac{1}{\beta}}\bar{K}^*=\left(\frac{\sigma}{\gamma+\sigma}\right)\left(\frac{\bar{L}+\bar{L}^*}{\eta\bar{L}+\eta^*\bar{L}^*}\right)\left(\frac{\bar{K}^*}{\bar{K}+\bar{K}^*}\right) \tag{59}$$

Aggregate emissions are given by

$$\hat{D}=\left(\frac{\sigma}{\gamma+\sigma}\right)\left(\frac{\bar{L}+\bar{L}^*}{\eta\bar{L}+\eta^*\bar{L}^*}\right)=\left(\frac{\sigma}{\gamma+\sigma}\right)\left(\frac{\frac{\bar{L}}{\bar{L}^*}+1}{\eta\frac{\bar{L}}{\bar{L}^*}+\eta^*}\right) \tag{60}$$

5.2. Autarchy equilibrium solution

Thus, in autarchy optimal emissions are set such that marginal domestic damages from emissions equal marginal domestic benefits. Solving for $\hat{d}^{NT}$ and $\hat{d}^{NT*}$ from (50) and (52) we obtain

$$\hat{d}^{NT}=\left(\frac{1-\beta}{\eta}\frac{\hat{p}_E^{NT}}{\hat{p}_A^{NT}}\frac{1}{\bar{L}}\right)^{\frac{1}{\beta}}\bar{K}, \qquad \hat{d}^{NT*}=\left(\frac{1-\beta}{\eta^*}\frac{\hat{p}_E^{NT*}}{\hat{p}_A^{NT*}}\frac{1}{\bar{L}^*}\right)^{\frac{1}{\beta}}\bar{K}^* \tag{61}$$

Using the market clearing condition of good E in each country we obtain the autarchy-relative prices $\frac{\hat{p}_E^{NT}}{\hat{p}_A^{NT}}$ and $\frac{p_E^{NT*}}{p_A^{NT*}}$, respectively, for the South and North which are given by,

$$\frac{p_E^{NT}}{p_A^{NT}}=\frac{\sigma^{\beta}}{1-\beta}\left(\frac{\frac{\gamma}{\eta}+\sigma\left(\frac{1}{\eta}-\frac{1}{\eta^*}\right)}{\gamma+2\sigma}\right)^{\beta}\frac{1}{\gamma^{\beta}}\frac{\eta\bar{L}}{\bar{K}^{\beta}} \tag{62}$$

$$\frac{p_E^{NT*}}{p_A^{NT*}}=\frac{\sigma^{\beta}}{1-\beta}\left(\frac{\frac{\gamma}{\eta^*}+\sigma\left(\frac{1}{\eta^*}-\frac{1}{\eta}\right)}{\gamma+2\sigma}\right)^{\beta}\frac{1}{\gamma^{\beta}}\frac{\eta^*\bar{L}^*}{\left(\bar{K}^*\right)^{\beta}} \tag{63}$$

Substituting (62) and (63) into (61) we obtain the emission levels in autarchy, given by,

$$d^{NT} = \left(\frac{\frac{\gamma}{\eta} + \sigma \left(\frac{1}{\eta} - \frac{1}{\eta^*} \right)}{\gamma + 2\sigma} \right) \frac{\sigma}{\gamma}, \qquad d^{NT*} = \left(\frac{\frac{\gamma}{\eta^*} + \sigma \left(\frac{1}{\eta^*} - \frac{1}{\eta} \right)}{\gamma + 2\sigma} \right) \frac{\sigma}{\gamma} \tag{64}$$

Since emissions must be positive in the South and North (if a country's emissions equal zero its production of good E and consumer's utility would equal zero) an autarchic equilibrium only exists when $\gamma + \sigma \left(\frac{\eta^* - \eta}{\eta^*} \right) > 0$ and $\gamma + \sigma \left(\frac{\eta - \eta^*}{\eta} \right) > 0$.

While emissions in the South are negatively affected by η they are positively affected by η^*. A possible explanation for this behavior is that if the South is largely affected by the pollution externality (relatively large η) emissions will be set at a relatively low level. The North, knowing that the South will pollute less, will pollute more to boost sector E's production. While sector A in the North will be affected by such increase in emissions this is counterbalanced as the South pollute less. Total emissions in autarchy therefore equal $D^{NT} \equiv d^{NT} + d^{NT*}$

$$D^{NT} = \frac{\sigma}{\gamma + 2\sigma} \left(\frac{1}{\eta} + \frac{1}{\eta^*} \right) \tag{65}$$

5.3. Trade effects on welfare and pollution

In this section we analyze the impact of international trade on welfare and aggregate emissions by comparing welfare levels and global emissions under trade and autarchy.

Proposition 6 *Aggregate emissions under autarchy are always larger than aggregate emissions with trade.*

Proof. the difference between emissions under trade and autarchy $\left(Z - Z^A\right)$ is given by

$$D - D^{NT} = -J \left[\eta^* \eta^* \underbrace{\left(\gamma + \sigma \frac{\eta^* - \eta}{\eta^*} \right)}_{B} \bar{L}^* + \eta\eta \underbrace{\left(\gamma + \sigma \frac{\eta - \eta^*}{\eta} \right)}_{R} \bar{L} \right] \tag{66}$$

where

$$J = \left(\frac{\sigma}{\gamma + \sigma} \right) \left(\frac{1}{\eta\eta^*} \right) \left(\frac{1}{\gamma + 2\sigma} \right) \left(\frac{1}{\eta\bar{L} + \eta^* \bar{L}^*} \right) > 0 \tag{67}$$

Notice that emissions in the South and North under autarchy can be rewritten as

$$d^{NT} = \frac{\sigma}{\gamma\eta}\left(\frac{\gamma+\sigma\left(\frac{\eta^*-\eta}{\eta^*}\right)}{\gamma+2\sigma}\right), \qquad d^{NT*} = \frac{\sigma}{\gamma\eta^*}\left(\frac{\gamma+\sigma\left(\frac{\eta-\eta^*}{\eta}\right)}{\gamma+2\sigma}\right) \tag{68}$$

If $\eta^*-\eta$ is negative $d^{NT}>0$ requires $\gamma+\sigma\left(\frac{\eta^*-\eta}{\eta^*}\right)>0$. Thus, γ must be grater than $\sigma\left(\frac{\eta^*-\eta}{\eta^*}\right)$. Hence, B is positive and R is trivially positive ($\eta^*-\eta<0 \Rightarrow \eta-\eta^*>0$). If, however, $\eta^*-\eta$ is positive then B is positive, and $d^{NT*}>0$ requires $\gamma+\sigma\left(\frac{\eta-\eta^*}{\eta}\right)>0$, thus R is positive. Therefore, $D-D^{NT}$ is always negative■

The reason for this is that with international trade all the marginal damages from emissions are considered while in the autarchic case only domestic marginal damages are taken into consideration when choosing the optimal level of emissions.

5.4. *Welfare*

We now investigate whether or not trade leads to larger welfare gains when compared to autarchy. Considering that emission-permits revenues are transferred in their entirety (τD) to a single country's representative consumer, we investigate whether such transfers are sufficient to make this consumer always better off in trade than in autarchy. First we look at the case of international trade. Without loss of generality we assume the North to receive all revenues from emissions ($T^*=\tau D$) as a lump-sum transfer. The income of the North with trade equals

$$r^*\bar{K}^* + w^*\bar{L}^* + T^* = r^*\bar{K}^* + w^*\bar{L}^* + \tau D \tag{69}$$

whereas the income of the representative consumer of the South is given by

$$r\bar{K} + w\bar{L} + T = r\bar{K} + w\bar{L} + 0. \tag{70}$$

In autarchy, we assume that each government passes the revenues from collected emission permits to its representative consumer as a lump-sum transfer. That is, the representative consumer of the South receives $T^{NT} = \tau^{NT}d^{NT}$ while the representative consumer of the North receives $T^{NT*} = \tau^{NT*}d^{NT*}$.

Let $\bar{L}^W = \bar{L}+\bar{L}^*$ and $\bar{K}^W = \bar{K}+\bar{K}^*$ and $H=\eta\bar{L}+\eta^*\bar{L}^*$ one can verify that welfare in the South under trade equals

$$V \equiv \hat{c}_A^{\gamma}\hat{c}_E^{1-\gamma} = Q\left(\bar{L} + \frac{\sigma\bar{L}^W}{\gamma+\sigma}\left[\frac{\beta}{1-\beta}\frac{\bar{K}}{\bar{K}^W} - \frac{\eta\bar{L}}{H}\right]\right) \tag{71}$$

while in the North welfare equals

$$V^{*} \equiv \hat{c}_{A}^{*\gamma} \hat{c}_{E}^{*1-\gamma} = Q\left(\bar{L}^{*} + \frac{\sigma \bar{L}^{W}}{\gamma + \sigma}\left[\frac{\bar{K}^{*} + (1-\beta)\,\bar{K}}{(1-\beta)\,\bar{K}^{W}} - \frac{\eta^{*}\bar{L}^{*}}{H}\right]\right) \tag{72}$$

where

$$Q = \gamma^{\gamma}\left(\gamma+\sigma\right)^{\beta(1-\gamma)}\left(\frac{\bar{K}^{W}}{\bar{L}^{W}}\right)^{\beta(1-\gamma)}\left(\frac{\sigma}{H}\right)^{\sigma}. \tag{73}$$

In autarchy, welfare in the South is given by

$$V^{NT} \equiv \left(c_{A}^{NT}\right)^{\gamma}\left(c_{E}^{NT}\right)^{1-\gamma} = \left(\frac{\sigma}{\gamma\eta}\right)^{\sigma}\frac{\bar{K}^{\beta(1-\gamma)}\bar{L}^{\gamma}}{\left(\gamma+2\sigma\right)^{1-\beta(1-\gamma)}}\left(\frac{\gamma\eta^{*} + \sigma\left(\eta^{*}-\eta\right)}{\eta^{*}}\right)^{1-\beta(1-\gamma)} \tag{74}$$

and for the North

$$V^{NT*} \equiv \left(c_{A}^{*NT}\right)^{\gamma}\left(c_{E}^{*NT}\right)^{1-\gamma} = \left(\frac{\sigma}{\gamma\eta^{*}}\right)^{\sigma}\frac{\bar{K}^{*\beta(1-\gamma)}\bar{L}^{*\gamma}}{\left(\gamma+2\sigma\right)^{1-\beta(1-\gamma)}}\left(\frac{\gamma\eta + \sigma\left(\eta-\eta^{*}\right)}{\eta}\right)^{1-\beta(1-\gamma)} \tag{75}$$

Proposition 7. *If*

i) an autarchic equilibrium exists;

ii) $\bar{K} = \bar{K}^{*}$ *and* $\bar{L} = \bar{L}^{*}$; *and*

iii) if with international trade emission-permit revenues (τD) *are—in their entirety—passed to the representative consumer of the North;*

then for sufficiently large η *and* β *the North is better off in autarchy than in trade.*

Proof. Let $\bar{K} = \bar{K}^{*}$ and $\bar{L} = \bar{L}^{*}$. For $\bar{K} = \bar{K}^{*}$ and $\bar{L} = \bar{L}^{*}$ with international trade welfare in the North is given by

$$V^{*} = \frac{\sigma^{\sigma}\bar{K}^{*\beta(1-\gamma)}\bar{L}^{*\gamma}\gamma^{\gamma}}{\left(\gamma+\sigma\right)^{1-\beta(1-\gamma)}}\frac{\left(2\sigma\eta+\eta+\eta^{*}\right)}{\left(\eta+\eta^{*}\right)^{\sigma+1}} \tag{76}$$

and in autarchy welfare in the North equals

$$V^{NT*} = \frac{\sigma^{\sigma}\bar{K}^{*\beta(1-\gamma)}\bar{L}^{*\gamma}}{\gamma^{\sigma}\eta^{*\sigma}\left(\gamma+2\sigma\right)^{1-\beta(1-\gamma)}}\left(\frac{\gamma\eta+\sigma\left(\eta-\eta^{*}\right)}{\eta}\right)^{1-\beta(1-\gamma)} \tag{77}$$

Since $\eta < \eta^{*}\frac{\gamma+\sigma}{\sigma}$ must hold for an autarchic equilibrium to exist we now make η as large as it can be by taking the limit of $V^{*} - V^{NT*}$ as η approaches $\frac{\gamma+\sigma}{\sigma}\eta^{*}$

$$\lim_{\eta \to \frac{\gamma+\sigma}{\sigma}\eta^*} \left(V^* - V^{NT*}\right) = \frac{\sigma^\sigma \bar{K}^{*\beta(1-\gamma)} \bar{L}^{*\gamma}\gamma^\gamma}{\eta^{*\sigma} \left(\gamma+\sigma\right)^{1-\beta(1-\gamma)}} Z \tag{78}$$

where

$$Z = \sigma^\sigma \frac{\left(2\sigma\left(\gamma+\sigma\right) + \left(\gamma+2\sigma\right)\right)}{\left(\gamma+2\sigma\right)^{\sigma+1}} - 1 \text{ with } \sigma = \left(1-\beta\right)\left(1-\gamma\right) \tag{79}$$

All that remains is to verify if for admissible values of *beta* and *gamma* Z is negative. For example $\beta = .9$ and $\gamma = .3$ would do so■

In figure 1 we have plotted Z for values of γ and β between zero and one (grey plane), and have also plotted the "zero"plane to more easily identify if Z is negative. Clearly, many values of β and γ make Z negative.

Figure 1. Values of Z for possible values of $(1-\beta)$ and γ

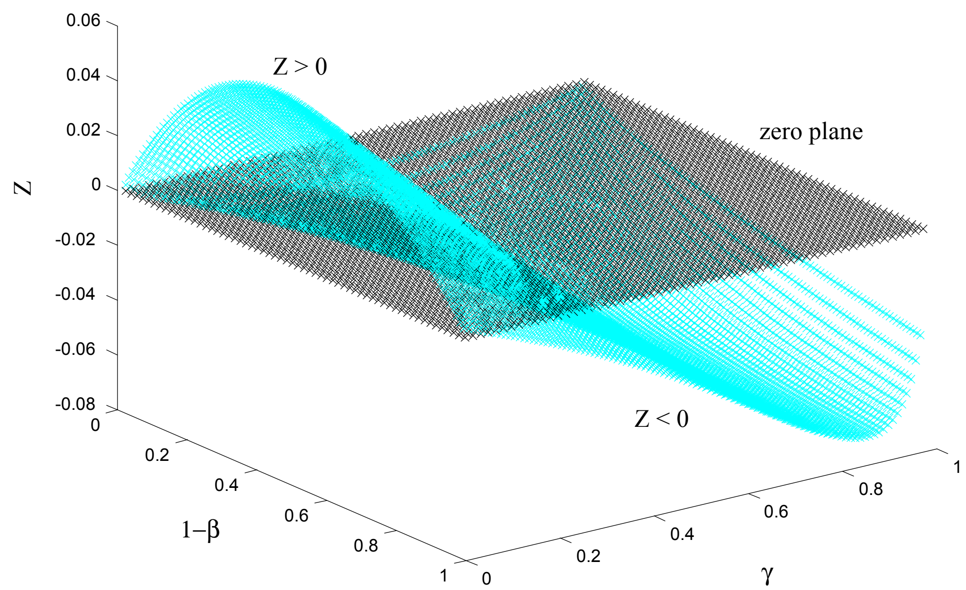
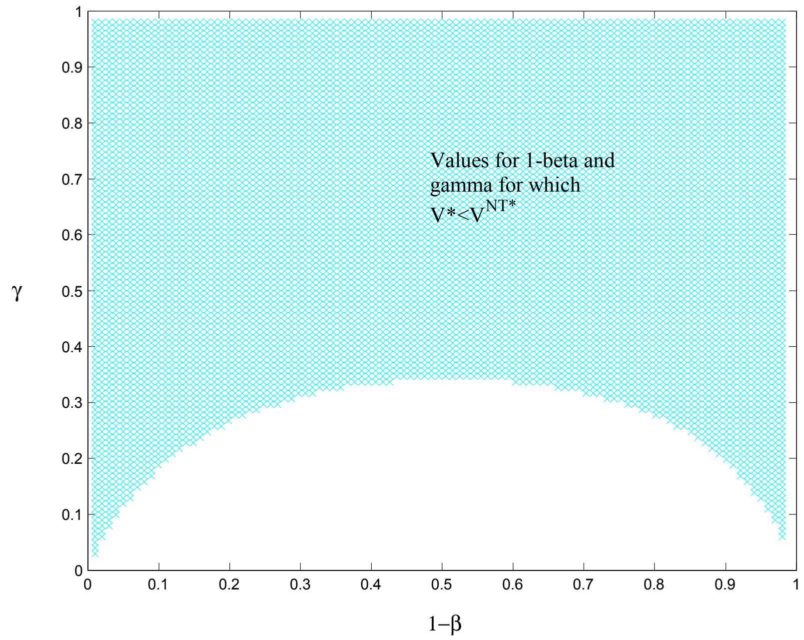


Figure 2. Values of $(1-\beta)$ and γ for which the North is better off in autarchy



The shaded area in figure 2 exhibits the values of $(1-\beta)$ and γ for which welfare in the North is larger in autarchy than in trade $(Z<0)$. Notice that for sufficiently large γ the North is always better off in autarchy than in trade.

Notice that autarchy may be better than trade even when full compensation from emissions damages takes place. The explanation for this is that if the South's vulnerable sector is largely susceptible to emissions with an international trade regime a tight environmental policy is set in place. The North in autarchy will set a loose environmental policy allowing for a relatively high amount of emissions, thus, boosting the production of the emitting good. The effects of this policy on the South, with a highly vulnerable sector, will be to choose a tight environmental policy, thus boosting the vulnerable sector's production in the North. The benefit of this feedback is larger the larger γ (the share of good A in the consumption expenditure) is as indicated in figure 2. It is possible that the costs of a tight policy with trade are sufficiently large so that even if all emission permits revenues are transferred to the North this country would be better off in autarchy than in trade.

We have also performed numerical simulations for the settings presented in sections two, three and four where capital and labor are employed in the production of goods A and E. We find that of our results still hold.

By no means we want to indicate that autarchy is desirable. The proposition indicates that if only emission-permits' revenues are used as transfers then for one country autarchy may be better than trade. As in standard trade theory there should be a sufficiently large transfer that leaves everyone better off as the result of trade. That gives room for other policy instruments to be used that could enable making larger transfers across countries, we however leave that for future research.

6. Conclusion

We analyze the impact of international trade with trans-boundary pollution and endogenous environmental policy on welfare and on the level of global emissions. We specially analyze the scenario where pollution externalities affect industrial output which has largely been neglected in the literature. Our analysis focuses on the case when pollution is emitted by some industries which affects the output of domestic and foreign industries.

When international trade in final goods is allowed we analyze two scenarios regarding emission policy; first, a centralized framework with internationally-tradable emission permits where a social planner chooses the level of emissions; second, a decentralized scenario where each country chooses the level of emissions that maximizes domestic welfare. We compare the trade cases with each other and with the case of autarchy—where there is no international trade neither in goods nor in emission permits and where each country sets environmental policy as to maximize domestic welfare.

We find that with international trade in final goods emission levels and emission-permit prices of the decentralized and centralized frameworks are equal. In the decentralized framework, as long as there is international trade in final goods, the individual countries' environmental policy always takes into account all marginal damages from emissions. Thus, in the decentralized framework prices of emission permits are equal across countries even in the absence of international trade in permits.

The importance of this result is that *i)* as long as pollution only affects production; *ii)* there is free international trade in final goods (international trade in permits is not necessary) and; *iii)* emissions are set optimally by individual countries then no agreement on environmental policy is necessary among countries. That is, an international agreement on environmental policy is not compulsory if there is undistorted trade at least in the pollution affected sectors. Thus, further integration of the commodity markets and further international trade agreements are desirable for mitigating environmental problems.

While one of the most vulnerable sectors to environmental problems is the agricultural sector this sector is also one of the least integrated sectors into world markets. According to our analysis if countries independently choose their environmental policy international trade in goods suffices such that all marginal damages from emissions are accounted for. This result also indicates that opening the borders for agricultural goods and other vulnerable goods can alleviate environmental problems.

We then compare the trade and autarchy scenarios. In some instances a representative consumer may be better off in autarchy than in trade—even if under trade he or she receives as a lump-sum transfer the entire emission-permit revenues. This occurs despite the fact that environmental policy with international trade accounts for all the marginal damages from emissions, whereas environmental policy in autarchy does not. This may occur when one country's vulnerable sector is largely susceptible to emissions. A country in autarchy and with a sector relatively less vulnerable to emissions will set a loose environmental policy allowing for a relatively high amount of emissions, thus, boosting the production of the emitting good. The effects of this policy on the country with the highly vulnerable sector will be to choose a tight environmental policy, thus boosting the sectors sensitive to emissions in the country with low vulnerability. If the country with low vulnerable sectors now chooses an international trade regime a tighter environmental policy is set in place. It is possible that the costs of this tighter policy are sufficiently large so that even if all emission permits revenues—that by large compensate for emission damages—are transferred to this country, this economy would be better off in autarchy than in trade.

By no means we want to indicate that autarchy is desirable. Our proposition indicates that if only emission-permits' revenues are used as transfers then for one country autarchy may be better than trade. As in standard trade theory there should be a sufficiently large transfer that leaves everyone better off as the result of trade. This gives room for other policy instruments to be used that could enable making larger transfers across countries. We, however, leave that for future research.

Appendix

Proof of proposition 1. The Lagrangian associated with problem (40) equals

$$
\begin{aligned}
\mathcal{L} \;=\;& U\left(c_A, c_E\right) && (80)\\
&+\phi_A\left(\left(1-\eta\left(d+d^*\right)\right)\left(K_A^{\alpha} L_A^{1-\alpha}\right)+\left(1-\eta^*\left(d+d^*\right)\right)\left(K_A^*\right)^{\alpha}\left(L_A^*\right)^{1-\alpha}-c_A-c_A^*\right) &&\\
&+\phi_E\left(\left(K_E^{\varepsilon} L_E^{1-\varepsilon}\right)^{\beta} d^{1-\beta}+\left(\left(K_E^*\right)^{\varepsilon}\left(L_E^*\right)^{1-\varepsilon}\right)^{\beta}\left(d^*\right)^{1-\beta}-c_E-c_E^*\right) && (81)\\
&+\delta_K\left(\bar{K}-K_A-K_E\right)+\delta_L\left(\bar{L}-L_A-L_E\right) &&
\end{aligned}
$$

where ϕ_A, ϕ_E, δ_K and δ_L are Lagrange multipliers.

An optimal solution associated with problem (40) must satisfy

$$
\frac{U_{c_A}\left(\underline{c}_A, \underline{c}_E\right)}{U_{c_E}\left(\underline{c}_A, \underline{c}_E\right)}=\frac{\underline{\phi}_A}{\underline{\phi}_E} \qquad (82)
$$

Let $\underline{MB}$ denote the marginal benefits from emissions in the South

$$
\underline{MB}=\underline{\phi}_E(1-\beta) \frac{\left(\underline{K}_E^{\varepsilon} \underline{L}_E^{1-\varepsilon}\right)^{\beta} \underline{d}^{1-\beta}}{\underline{d}} \leq \underline{\phi}_A\left(\eta\left(\underline{K}_A^{\alpha} \underline{L}_A^{1-\alpha}\right)+\eta^*\left(\underline{K}_A^*\right)^{\alpha}\left(\underline{L}_A^*\right)^{1-\alpha}\right) \qquad (83)
$$

if $\underline{d} > 0$ then (83) holds with equality. Notice that even if each government independently and selfishly chooses the optimal-domestic level of emissions, international trade in final goods ensures that all—domestic and foreign—marginal damages from domestic emissions equal their marginal benefits. Thus, the decentralized environmental policy is consistent with the centralized environmental policy. The first order conditions associated with capital and labor use in the production of goods A and E equal

$$
\begin{aligned}
\frac{\alpha \underline{\phi}_A\left(1-\eta\left(\underline{d}+\underline{d}^*\right)\right) \underline{K}_A^{\alpha} \underline{L}_A^{1-\alpha}}{\underline{K}_A} &\leq \underline{\delta}_K, && (84)\\
\frac{(1-\alpha) \underline{\phi}_A\left(1-\eta\left(\underline{d}+\underline{d}^*\right)\right) \underline{K}_A^{\alpha} \underline{L}_A^{1-\alpha}}{\underline{L}_A} &\leq \underline{\delta}_L, && (85)
\end{aligned}
$$

$$
\begin{aligned}
\frac{\beta \varepsilon \underline{\phi}_E\left(\underline{K}_E^{\varepsilon} \underline{L}_E^{1-\varepsilon}\right)^{\beta} \underline{d}^{1-\beta}}{\underline{K}_E} &\leq \underline{\delta}_K, && (86)\\
\frac{\beta(1-\varepsilon) \underline{\phi}_E\left(\underline{K}_E^{\varepsilon} \underline{L}_E^{1-\varepsilon}\right)^{\beta} \underline{d}^{1-\beta}}{\underline{L}_E} &\leq \underline{\delta}_L. && (87)
\end{aligned}
$$

If production of commodities A and E occurs then (84) − (85) and (86) − (87), respectively, hold with equality, and emissions are given by

$$\underline{d} = \left(\frac{\underline{\phi}_E}{\underline{\phi}_A}\right)^{\frac{1}{\beta}} \left(\frac{1-\beta}{\eta\left(\underline{K}_A^{\alpha}\underline{L}_A^{1-\alpha}\right) + \eta^*\left(\underline{K}_A^*\right)^{\alpha}\left(\underline{L}_A^*\right)^{1-\alpha}}\right)^{\frac{1}{\beta}} \left(\underline{K}_E^{\varepsilon}\underline{L}_E^{1-\varepsilon}\right)$$

The competitive solution for the South is found by setting $\frac{\underline{\phi}_A}{\underline{\phi}_E} = \frac{\underline{p}_A}{\underline{p}_E}$, $\underline{\delta}_K = \underline{r}$, $\underline{\delta}_L = \underline{w}$. If sector E in the South is open then sectoral optimality requires that the value of the marginal physical product from emissions equals the price of an emission permit

$$\underline{p}_E\left(1-\beta\right)\frac{\left(\underline{K}_E^{\varepsilon}\underline{L}_E^{1-\varepsilon}\right)^{\beta}\underline{d}^{1-\beta}}{\underline{d}} = \underline{\tau} \tag{88}$$

Equations (83) and (88) imply

$$\underline{\tau} = \underline{p}_E\left(1-\beta\right)\frac{\left(\underline{K}_E^{\varepsilon}\underline{L}_E^{1-\varepsilon}\right)^{\beta}}{\underline{d}^{\beta}} = \underline{p}_A\left(\eta\left(\underline{K}_A^{\alpha}\underline{L}_A^{1-\alpha}\right) + \eta^*\left(\underline{K}_A^*\right)^{\alpha}\left(\underline{L}_A^*\right)^{1-\alpha}\right) \tag{89}$$

Similarly for a country in the North we have

$$\begin{aligned}
\mathcal{L} \;=\;& U\left(c_{*A}, c_E^*\right) && (90)\\
&+\phi_A^*\left(\left(1-\eta\left(d+d^*\right)\right)\left(K_A^{\alpha}L_A^{1-\alpha}\right) + \left(1-\eta^*\left(d+d^*\right)\right)\left(K_A^*\right)^{\alpha}\left(L_A^*\right)^{1-\alpha} - c_A - c_A^*\right)\\
&+\phi_E^*\left(\left(K_E^{\varepsilon}L_E^{1-\varepsilon}\right)^{\beta}d^{1-\beta} + \left(\left(K_E^*\right)^{\varepsilon}\left(L_E^*\right)^{1-\varepsilon}\right)^{\beta}\left(d^*\right)^{1-\beta} - c_E - c_E^*\right) && (91)\\
&+\delta_K^*\left(\bar{K}^* - K_A^* - K_E^*\right) + \delta_L^*\left(\bar{L}^* - L_A^* - L_E^*\right)
\end{aligned}$$

where ϕ_A^*, ϕ_E^*, δ_K^* and δ_L^* are Lagrange multipliers. Optimality with regard to $\underline{c}_A^*$ and $\underline{c}_E^*$ implies $\frac{U_{c_A^*}\left(\underline{c}_A^*,\underline{c}_E^*\right)}{U_{c_E^*}\left(\underline{c}_A^*,\underline{c}_E^*\right)} = \frac{\underline{\phi}_A^*}{\underline{\phi}_E^*}$ and with regard to $\underline{d}^*$ implies

$$\underline{\phi}_E^*\left(1-\beta\right)\frac{\left(\underline{K}_E^{*\varepsilon}\underline{L}_E^{*1-\varepsilon}\right)^{\beta}}{\underline{d}^{*\beta}} \le \underline{\phi}_A^*\left(\eta\left(\underline{K}_A^{\alpha}\underline{L}_A^{1-\alpha}\right) + \eta^*\left(\underline{K}_A^*\right)^{\alpha}\left(\underline{L}_A^*\right)^{1-\alpha}\right) \text{ if } \underline{d}^* > 0 \text{ then equal} \tag{92}$$

To avoid redundancy we omit writing the remaining first order condition of the government of the North but similar expressions as (84) − (87) hold.

The competitive solution for the North is also found by setting $\frac{\underline{\phi}_A^*}{\underline{\phi}_E^*} = \frac{\underline{p}_A^*}{\underline{p}_E^*}$, $\delta_K^* = r^*$, $\delta_L^* = w^*$. If production of commodity E takes place then we get

$$\underline{\tau}^* = \underline{p}_E^* \frac{(1-\beta)\left(\underline{K}_E^{*\varepsilon} \underline{L}_E^{*1-\varepsilon}\right)^{\beta}}{\underline{d}^{*\beta}} = \underline{p}_A \left(\eta \left(\underline{K}_A^{\alpha} \underline{L}_A^{1-\alpha}\right) + \eta^* \left(\underline{K}_A^*\right)^{\alpha} \left(\underline{L}_A^*\right)^{1-\alpha}\right) \tag{93}$$

Notice that as long as there is free international trade in final goods, and transportation costs and trade barriers are absent final goods are traded at equal prices across countries, thus $\frac{\underline{p}_A^*}{\underline{p}_E^*} = \frac{\underline{p}_A}{\underline{p}_E}$. It follows from equations (89) and (93) that if good E is produced in both countries the price of emission permits is equal across countries.

Notice that all of the first order conditions of the centralized and decentralized scenarios are equal and all market clearing conditions regarding final goods and factors of production must hold in either equilibrium, that is equations (20), (21), (23) and (24) must hold. It must be the case that equilibrium prices, emissions and labor and capital allocations are equal under the centralized and decentralized frameworks.

We now sketch the procedure to find an equilibrium solution when specialization does not occur.

The first order conditions associated with sectoral optimization are given by

$$K_A = \alpha \frac{p_A}{r} Y_A \qquad K_E = \beta\varepsilon \frac{p_E}{r} Y_E \tag{94}$$

$$L_A = (1-\alpha) \frac{p_A}{w} Y_A \qquad L_E = \beta(1-\varepsilon) \frac{p_E}{w} Y_E \tag{95}$$

$$K_A^* = \alpha \frac{p_A}{r^*} Y_A^* \qquad K_E^* = \beta\varepsilon \frac{p_E}{r^*} Y_E^* \tag{96}$$

$$L_A^* = (1-\alpha) \frac{p_A}{w^*} Y_A^* \qquad L_E^* = \beta(1-\varepsilon) \frac{p_E}{w^*} Y_E^* \tag{97}$$

The market clearing conditions for capital and labor services then equal

$$K_A + K_E = \alpha \frac{p_A}{r} Y_A + \varepsilon\beta \frac{p_E}{r} Y_E = \bar{K} \tag{98}$$

$$L_A + L_E = (1-\alpha) \frac{p_A}{w} Y_A + (1-\varepsilon)\beta \frac{p_E}{w} Y_E = \bar{L} \tag{99}$$

$$K_A^* + K_E^* = \alpha \frac{p_A}{r^*} Y_A^* + \varepsilon\beta \frac{p_E}{r^*} Y_E^* = \bar{K}^* \tag{100}$$

$$L_A^* + L_E^* = (1-\alpha) \frac{p_A^*}{w^*} Y_A + (1-\varepsilon)\beta \frac{p_E}{w^*} Y_E^* = \bar{L}^* \tag{101}$$

Solving equations (98) and (99) simultaneously we can solve for Y_A and Y_E in terms of p_A, r, and w and the capital and labor endowments of the South. Similarly, (100) and (101) can be used to solve for Y_A^* and Y_E^* in terms of p_A, r^* and w^* and the capital and labor endowments of the North.

More precisely,

$$Y_A = \frac{\varepsilon w\bar{L} - (1-\varepsilon) r\bar{K}}{(\varepsilon-\alpha) p_A} \qquad Y_E = \frac{\alpha w\bar{L} - (1-\alpha) r\bar{K}}{(\alpha-\varepsilon) \beta p_E} \tag{102}$$

$$Y_A^* = \frac{\varepsilon w^*\bar{L}^* - (1-\varepsilon) r^*\bar{K}^*}{(\varepsilon-\alpha) p_A} \qquad Y_E^* = \frac{\alpha w^*\bar{L}^* - (1-\alpha) r^*\bar{K}^*}{(\alpha-\varepsilon) \beta p_E} \tag{103}$$

Substituting (102) and (103) into (94) − (97) we can then express factor allocation in terms of factor prices as follows

$$K_A = \left(\frac{\alpha}{\varepsilon-\alpha}\right) \frac{\varepsilon w\bar{L} - (1-\varepsilon) r\bar{K}}{r}, \qquad K_E = \left(\frac{\varepsilon}{\alpha-\varepsilon}\right) \frac{\alpha w\bar{L} - (1-\alpha) r\bar{K}}{r} \tag{104}$$

$$L_A = \left(\frac{1-\alpha}{\varepsilon-\alpha}\right) \frac{\varepsilon w\bar{L} - (1-\varepsilon) r\bar{K}}{w}, \qquad L_E = \left(\frac{1-\varepsilon}{\alpha-\varepsilon}\right) \frac{\alpha w\bar{L} - (1-\alpha) r\bar{K}}{w} \tag{105}$$

$$K_A^* = \left(\frac{\alpha}{\varepsilon-\alpha}\right) \frac{\varepsilon w^*\bar{L}^* - (1-\varepsilon) r^*\bar{K}^*}{r^*}, \qquad K_E^* = \left(\frac{\varepsilon}{\alpha-\varepsilon}\right) \frac{\alpha w^*\bar{L}^* - (1-\alpha) r^*\bar{K}^*}{r^*} \tag{106}$$

$$L_A^* = \left(\frac{1-\alpha}{\varepsilon-\alpha}\right) \frac{\varepsilon w^*\bar{L}^* - (1-\varepsilon) r^*\bar{K}^*}{w^*}, \qquad L_E^* = \left(\frac{1-\varepsilon}{\alpha-\varepsilon}\right) \frac{\alpha w^*\bar{L}^* - (1-\alpha) r^*\bar{K}^*}{w^*} \tag{107}$$

Using (31) τ can be solve in terms of p_A, r, w, r^*, w^*, capital and labor endowments as follows

$$\begin{aligned} \tau &= p_A \left(\eta \left(K_A^\alpha L_A^{1-\alpha}\right) + \eta^* \left(K_A^*\right)^\alpha \left(L_A^*\right)^{1-\alpha}\right) \\ &= \frac{\alpha^\alpha (1-\alpha)^{1-\alpha} p_A}{(\varepsilon-\alpha)} \left(\frac{\eta \left(\varepsilon w\bar{L} - (1-\varepsilon) r\bar{K}\right)}{r^\alpha w^{1-\alpha}} + \frac{\eta^* \left(\varepsilon w^*\bar{L}^* - (1-\varepsilon) r^*\bar{K}^*\right)}{r^{*\alpha} w^{*1-\alpha}}\right) \end{aligned} \tag{108}$$

Using (29) d can be solved in terms of p_E, r, w and factor endowments such that

$$\begin{aligned} d &= \left(\frac{p_E (1-\beta)}{\tau}\right)^{\frac{1}{\beta}} \hat{K}_E^\varepsilon \hat{L}_E^{1-\varepsilon} \\ &= \left(\frac{(1-\beta) p_E}{\tau}\right)^{\frac{1}{\beta}} \frac{\varepsilon^\varepsilon (1-\varepsilon)^{1-\varepsilon}}{r^\varepsilon w^{1-\varepsilon}} \frac{\alpha w\bar{L} - (1-\alpha) r\bar{K}}{(\alpha-\varepsilon)} \end{aligned} \tag{109}$$

where τ can be substituted out using (108). Similarly d^* can be solved in terms of p_E, r^*, w^* and factor endowments as follows

$$d^* = \left(\frac{(1-\beta) p_E}{\tau}\right)^{\frac{1}{\beta}} \frac{\varepsilon^\varepsilon (1-\varepsilon)^{1-\varepsilon}}{r^{*\varepsilon} w^{*1-\varepsilon}} \frac{\alpha w^*\bar{L}^* - (1-\alpha) r^*\bar{K}^*}{(\alpha-\varepsilon)} \tag{110}$$

where τ can be substituted out using (108).

Zero profits in sectors A and E in the South and North are given by

$$p_A = \frac{r^{\alpha} w^{1-\alpha}}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}(1-\eta D)}, \qquad p_A = \frac{r^{*\alpha} w^{*1-\alpha}}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}(1-\eta^{*} D)} \tag{111}$$

$$p_E = \frac{r^{\beta\varepsilon} w^{\beta(1-\varepsilon)} \tau^{1-\beta}}{\beta^{\beta}\varepsilon^{\beta\varepsilon}(1-\varepsilon)^{\beta(1-\varepsilon)}(1-\beta)^{1-\beta}}, \qquad p_E = \frac{r^{*\beta\varepsilon} w^{*\beta(1-\varepsilon)} \tau^{1-\beta}}{\beta^{\beta}\varepsilon^{\beta\varepsilon}(1-\varepsilon)^{\beta(1-\varepsilon)}(1-\beta)^{1-\beta}} \tag{112}$$

Substituting (108) – (110), these four equations implicitly define r, w, r^* and w^* in terms of p_A, p_E and factor endowments

Lets assume the distribution of revenues in the North and South in the centralized scenario to be equal to (T, T^*). Solving the optimization problems of consumers in the South and North the world demand of good A equals

$$\begin{aligned} c_A + c_A &= \frac{\gamma}{p_A}\left(\left(w\bar{L} + r\bar{K} + \hat{T}\right) + \left(w^*\bar{L}^* + r^*\bar{K}^* + \hat{T}^*\right)\right) \\ &= \frac{\gamma}{p_A}\left(p_A\left(Y_A + Y_A^*\right) + \hat{p}_E\left(Y_E + Y_E^*\right)\right) \end{aligned} \tag{113}$$

Notice that $T + T^* = \tau(d + d^*)$. Market clearing in good A $(c_A + c_A = Y_A + Y_A^*)$ implies

$$\frac{\gamma}{p_A}\left(p_A\left(Y_A + Y_A^*\right) + \hat{p}_E\left(Y_E + Y_E^*\right)\right) = Y_A + Y_A^* \tag{114}$$

or $\frac{p_E}{p_A}\left(Y_E + Y_E^*\right) = \left(Y_A + Y_A^*\right)\left(\frac{1-\gamma}{\gamma}\right)$. We can also solve in the same manner for the decentralized scenario.

Notice that the price ratios $\frac{\hat{p}_E}{\hat{p}_A}$, $\frac{p_E}{p_A}$ that solve for the centralized and decentralized frameworks must be the same. This concludes our proof■

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