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# FACTOR PRICE EQUALIZATION AND TRANSBOUNDARY POLLUTION REVISITED

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*Abstract*: This paper re-examines the effect of international trade on industrial pollution in a North-South trade model developed by Copeland and Taylor (1994, *Quarterly Journal of Economics* 109, pp. 755–787; 1995, *American Economics Review* 85, pp. 716–737), by extending the model to a case in which the pollution is neither necessarily local nor global. It is demonstrated that trade decreases pollution in the human-capital-abundant North and increases pollution in the human-capital-scarce South, irrespective of the degree of pollution spillover. It is also shown that the total pollution level in the world increases by opening trade, except for a case in which pollution is purely global.

**Key words:** North-South trade, transboundary pollution, environmental policy, factor price equalization
**JEL Classification Number:** F18, F11, Q58

## 1. INTRODUCTION

In the literature of trade and the environment, Copeland and Taylor (1994, 1995) provided an influential theoretical framework. They developed a general-equilibrium North-South trade model with a continuum of goods indexed by their emission intensity, with pollution causing negative effect on welfare, and with governments internalizing pollution externalities by environmental policy. The assumption that there is a continuum of goods rather than considering a simple two good economy allows us to analyze how trade affects pollution by changing a country's composition of goods. In addition, the assumptions that governments set pollution policy endogenously and that environmental quality is a normal good allows us to investigate trade-induced technique effects. These composition and technique effects are, in conjunction with the scale effect, useful in exploring how international trade affects pollution. They are also useful in connecting or comparing the theory with empirical studies by, e.g., Grossman and Krueger (1993).

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In Copeland and Taylor (1994), it is assumed that detrimental effects of pollution is purely local, i.e., there is no transboundary pollution. In Copeland and Taylor (1995), by contrast, the effects of pollution is assumed to be purely global, i.e., emissions of pollution in one country completely spill over to the other country. This paper re-examines the effect of international trade on industrial pollution in the Copeland-Taylor model by extending the model to a case in which the pollution is neither necessarily local nor global.

In the Copeland–Taylor model, production of goods requires one primary factor of production, the effective labor. However, it is also assumed that emission of pollution is inevitable; that is, if national government controls the emission of pollution generated by production process, private firms must pay for their emissions. This means that pollution can be treated as another factor input and hence the model becomes a version of multi-good, two-factor one. Assuming that each country has an access to the same production technologies, factor prices (i.e., wage rate and price of pollution) may or may not be equalized across countries.

In this paper, we focus attention on the free trade equilibrium in which factor prices are equalized between trading countries. In the global pollution model of Copeland and Taylor (1995), the free trade equilibrium with factor price equalization (FPE), as well as the non-FPE equilibrium, is examined in detail. By contrast, in the local pollution model of Copeland and Taylor (1994), the FPE equilibrium received less attention. In this paper, the degree of international spillover of pollution is given by a parameter $\delta \in [0, 1]$, and hence both the local pollution model (corresponding to $\delta = 0$) and the global pollution model (corresponding to $\delta = 1$) are treated as special cases. It is demonstrated in this extended model that trade decreases pollution in the human-capital-abundant North and increases pollution in the human-capital-scarce South, irrespective of the degree of pollution spillover. In addition, it is shown that the total pollution level in the world increases by opening trade, except for a case in which pollution is purely global, where total pollution is unaffected by trade.

## 2. THE COPELAND–TAYLOR MODEL WITH (IMPERFECT) SPILLOVER OF POLLUTION

We consider a world economy consisting of two countries, North and South. Southern variables are indicated by an asterisk (*). In each country, a continuum of goods indexed by $s \in [0, 1]$ is produced and consumed, and firms and consumers are competitive. There is one primary input, effective labor, employed in the production of each good. The production process generates, as a byproduct, emission of pollution. Pollution, which may or may not go beyond national borders, has a detrimental effect on consumer's utility, but has no productivity effects. The two countries are different in the level of human capital, represented by labor endowment in effective units. That is, we assume $L > L^*$, where $L$ ($L^*$) denotes the effective labor endowment in the North (South). All other aspects including preferences and technologies are assumed to be identical.

We assume the following functional relationship between the output $y(s)$, labor input $l$ and emission of pollution $z$:

$$y(s) = f(z, l; s) = \begin{cases} l^{1-\alpha(s)} z^{\alpha(s)} & \text{if} \quad z \leq \zeta\, l \\ 0 & \text{if} \quad z > \zeta\, l, \end{cases} \tag{1}$$

where $\zeta > 0$, and $\alpha(s) \in (0, 1)$ is a pollution intensity of each good, with $\alpha'(s) > 0$. Let us denote the wage rate by $w$ and the price that the firm must pay for the emission of pollution per unit by $\tau$, respectively. $\tau$ can be interpreted as a tax rate on pollution imposed by the national government, or price of a pollution permit if in each country there is a market for pollution permits. Each competitive firm determines, taking the factor prices $(w, \tau)$ as given, the levels of factor inputs in order to minimize the production costs, subject to the technological constraint or the "production function" given by (1). The unit cost function is derived as $c(w, \tau; s) = \kappa(s)\, \tau^{\alpha(s)} w^{1-\alpha(s)}$, where $\kappa(s) \equiv \alpha(s)^{-\alpha(s)}(1 - \alpha(s))^{-(1-\alpha(s))}$.

In each country there is a representative consumer who gains utility from consumption but suffers from pollution. Let us denote the consumption of good $s$ by $x(s)$ and the total pollution in the North (South) by $Z$ ($Z^*$), respectively, and suppose that the utility function of the representative consumer in the North is given by

$$U = \int_0^1 b(s) \ln x(s) ds - \frac{\beta(Z + \delta Z^*)^\gamma}{\gamma}, \tag{2}$$

where $\beta > 0$, $\gamma \geq 1$, $b(s) \in (0, 1)$ satisfies $\int_0^1 b(s)\, ds = 1$,[1] and $\delta \in [0, 1]$ denotes a spillover effect of foreign pollution on the home country's welfare, respectively. If $\delta = 0$, pollution is purely local, as assumed in Copeland and Taylor (1994). If $\delta = 1$, pollution is purely global, i.e., there is a perfect international spillover of pollution, as assumed in Copeland and Taylor (1995). Since the two countries are assumed to be symmetric, a representative consumer's utility in the South is given by (2), with $Z$ and $Z^*$ interchanged.

Let us denote the price of good $s$ by $p(s)$ and and the total income of the representative consumer in the North by $I$. The representative consumer determines the consumption of each good $x(s)$ in order to maximize his/her utility (2) subject to the budget constraint $\int_0^1 p(s)x(s)ds = I$, taking the price vector $\mathbf{p}$, income $I$ and pollution levels $Z$, $Z^*$ as given. This derives the indirect utility function as follows:

$$V(\mathbf{p}, I, Z, Z^*) = \int_0^1 b(s) \ln b(s) ds - \int_0^1 b(s) \ln p(s) ds + \ln I - \frac{\beta(Z + \delta Z^*)^\gamma}{\gamma}. \tag{3}$$

The emission of pollution by private firms in each country is controlled by the national government. There are two ways for the government's pollution policy that is cost effective; one is to determine the price of pollution $\tau$ by setting pollution tax, and the other is to establish a national market for emission permits and to determine the total supply of permits $Z$. In both cases, each private firm determines its emission level $z(s)$,

[1] From the first-order conditions for utility maximization and the budget constraint, the demand function for good $s$ can be derived as $x(s) = b(s)I/p(s)$. Thus, $b(s)$ is also equal to the expenditure share of good $s$.

$s \in [0, 1]$ as a function of $\tau$. In the former case, the national pollution level $\int_0^1 z(s)ds$ is endogenously determined. In the latter case, $\tau$ is endogenously determined by the market clearing condition $\int_0^1 z(s)ds = Z$. In what follows we assume that the governments use a system of tradable pollution permits as environmental policy, but similar discussions hold for the case of pollution tax policy. The objective of each government is to maximize the consumer's utility.

We assume that the revenue from the sales of pollution permits is transferred to the representative consumer in a lump-sum form. Because of linear homogeneity of the production function (1), the national income in the North equals the sum of labor income and revenue from the pollution permits $I = wL + \tau Z$. We assume that the government in each country does not attempt to use environmental policy to manipulate their terms of trade.[2] The Northern government then determines the supply of pollution permits $Z$ in order to maximize the indirect utility (3), taking the pollution level in the South $Z^*$ and the price vector $(\mathbf{p}, w, \tau)$ as given. Substituting $I = wL + \tau Z$ into (3) and maximizing it with respect to $Z$, we have $dV/dZ = V_I \tau + V_Z = 0$. Then, the price of pollution is derived as

$$\tau = -\frac{V_Z}{V_I} = \beta(Z + \delta Z^*)^{\gamma - 1} I. \tag{4}$$

In light of $I = wL + \tau Z$, (4) can be rewritten as

$$\rho \equiv \frac{\tau}{w} = \frac{\beta(Z + \delta Z^*)^{\gamma-1} L}{1 - \beta(Z + \delta Z^*)^{\gamma-1} Z}, \tag{5}$$

which indicates the relationship between the relative price of pollution (to the wage rate) $\rho$ and the "supply" of pollution determined by the Northern government. In other words, (5) defines the (inverse) supply curve for pollution in the North. It is clear from (5) that the pollution supply is increasing in $\rho$. The pollution supply curve in the South can be analogously derived.

## 3. ANALYSIS

### 3.1. Autarky

Under the autarky equilibrium, the domestic demand for each good equals to the domestic supply, $y(s) = x(s)$. In addition, from the cost-minimization condition in the case of Cobb-Douglas production function (1), we have $\tau z(s) = \alpha(s)p(s)y(s)$. Moreover, from the utility function (2), we obtain $p(s)x(s) = b(s)I$. Therefore, it follows that

$$\tau z(s) = \alpha(s)b(s)I, \qquad s \in [0, 1]. \tag{6}$$

Integrating (6), in light of $I = wL + \tau Z$, we have

$$\rho = \frac{\bar{\theta} L}{(1 - \bar{\theta})Z}, \qquad \bar{\theta} \equiv \int_0^1 \alpha(s)b(s)ds, \tag{7}$$

[2] Copeland and Taylor (1994) justifies this assumption on the ground of GATT/WTO rules. On the other hand, Copeland and Taylor (1995) assume that the world economy consists of $n$ Northern and $n^*$ Southern countries. By letting $n+n^*$ be sufficiently large, it is assumed that the government in each country determines its environmental policy ignoring its effect on the terms of trade.

which presents a relationship between the relative factor price and the "demand" for pollution. Since $0 < \bar{\theta} < 1$, the (inverse) demand for pollution is decreasing in $\rho$.

From (5) and (7), the following relationship holds at the intersection of the pollution demand curve and the pollution supply curve:

$$(Z + \delta Z^*)^{\gamma-1} Z = \bar{\theta}/\beta. \tag{8}$$

Eq. (8) signifies the market equilibrium level of pollution in the North, taking the pollution level in the South as given. In other words, (8) defines the North's reaction function of pollution. Analogously for the South, the pollution reaction function is defined, in the implicit form, as $(Z^* + \delta Z)^{\gamma-1} Z^* = \bar{\theta}/\beta$. By solving the pollution reaction functions of both countries simultaneously, we have the Nash equilibrium pollution levels under autarky.

PROPOSITION 1. *The equilibrium pollution levels in each country under autarky are*

$$Z_A = Z_A^* = \left[\frac{\bar{\theta}}{(1+\delta)^{\gamma-1}\beta}\right]^{1/\gamma} \tag{9}$$

*for* $\forall \delta \in [0, 1]$.

*Proof.* Consider first the case that pollution is purely local, i.e., $\delta = 0$. In this case, (8) can be rewritten as $Z^\gamma = \bar{\theta}/\beta$ and hence we have $Z_A = (\bar{\theta}/\beta)^{1/\gamma}$. Similar result holds for the South.

Next consider the case of $\delta \in (0, 1]$. Then, from the pollution reaction functions it follows that

$$(Z + \delta Z^*)^{\gamma-1} Z = \bar{\theta}/\beta = (Z^* + \delta Z)^{\gamma-1} Z^*. \tag{10}$$

Suppose $Z > Z^*$. Then, (10) implies that $(Z + \delta Z^*)^{\gamma-1} < (Z^* + \delta Z)^{\gamma-1}$ must hold. However, since $(Z+\delta Z^*)-(Z^*+\delta Z) = (1-\delta)(Z-Z^*) > 0$ when $Z > Z^*$ and $\gamma \geq 1$, $Z > Z^*$ and $(Z + \delta Z^*)^{\gamma-1} < (Z^* + \delta Z)^{\gamma-1}$ are not compatible. Assuming $Z < Z^*$ also leads to contradiction in a similar manner. Hence, it must hold that $Z = Z^*$ in the Nash equilibrium. Taking this into consideration, (10) yields (9). □

In this model, the equilibrium pollution level in each country under autarky is independent of the levels of human capital. This is because the scale effect, which is an increase in pollution created by an increase in the level of economic activity in a country, and the technique effect, which measures a decrease in aggregate pollution arising from a switch to less pollution-intensive production techniques, are canceled out.[3]

As for the autarky relative prices, $\rho_A$ and $\rho_A^*$, it holds that $\rho_A > \rho_A^*$. This is because $L > L^*$ by assumption and $Z_A = Z_A^*$ by Proposition 1. Intuitively, comparing with the South, pollution becomes a scarce input relative to labor in the North and hence its relative price is high. This means that the North (South) has a comparative advantage in the goods that is relatively labor-intensive (pollution-intensive). Note that this result is independent of the degree of pollution spillover.

[3] The remaining composition effect, which measures a change in pollution due to a change in the range of goods produced by a country, is absent in the present case with incomplete specialization and factor price equalization.

*3.2. Free Trade*

There are two kinds of free trade equilibrium, categorized by the possibility of factor price equalization (FPE). One is the non-FPE equilibrium, in which each good is produced in either of the two countries. The other is the FPE equilibrium, in which each good is produced in both countries. Following Copeland and Taylor (1994, Proposition 1; 1995, Proposition B1), we can show that if the two countries have sufficiently similar effective labor endowments, the FPE equilibrium is realized, as demonstrated by the following proposition.

PROPOSITION 2. *Factor prices are equalized between the two countries if and only if $L^* < L \leq \hat{\lambda} L^*$, where*

$$\hat{\lambda} \equiv \frac{\int_0^{\hat{s}} [1-\alpha(s)]b(s)ds}{\int_{\hat{s}}^1 [1-\alpha(s)]b(s)ds}$$

*and $\hat{s} \in (0, 1)$ is implicitly defined by*

$$\left[\frac{\delta \int_0^{\hat{s}} \alpha(s)b(s)ds + \int_{\hat{s}}^1 \alpha(s)b(s)ds}{\int_0^{\hat{s}} \alpha(s)b(s)ds + \delta \int_{\hat{s}}^1 \alpha(s)b(s)ds}\right]^{\gamma-1} \frac{\int_{\hat{s}}^1 b(s)ds}{\int_0^{\hat{s}} b(s)ds} \equiv 1.$$

*If $L > \hat{\lambda} L^*$, it holds that $\tau > \tau^*$ and the North specializes in relatively clean goods and the South specializes in pollution-intensive goods.*

*Proof.* See the Appendix.

In the non-FPE equilibrium, the pattern of trade in each country is determined, in a way such that the South completely specializes in relatively pollution-intensive goods whereas the North completely specializes in relatively clean and human-capital-intensive goods. In the FPE equilibrium, by contrast, the pattern of trade is indeterminate.[4] However, equalization of factor prices between the countries implies that free trade in goods is a complete substitutes for international factor mobility. This means that the pattern of factor content of trade can be determined even if the pattern of trade in each country is indeterminate, and hence the effect of trade on pollution level in each country can be analyzed.

The total level of pollution in the world in the FPE equilibrium is obtained at the intersection of the world demand curve and the world supply curve of pollution. In light of (7), the (inverse) world demand function of pollution is given by

$$\rho = \frac{\bar{\theta}(L + L^*)}{(1-\bar{\theta})(Z + Z^*)}. \tag{11}$$

The world supply function of pollution is, by contrast, difficult to present in an explicit form because we need to solve (5) and

$$\rho = \frac{\beta(Z^* + \delta Z)^{\gamma-1} L^*}{1 - \beta(Z^* + \delta Z)^{\gamma-1} Z^*}, \tag{12}$$

and then obtain the Nash equilibrium pollution level as a function of $\rho$.

[4] This is the typical result in trade theory if the number of goods is more than the number of inputs. See, for example, Ethier (1984).

LEMMA 1. *Let us denote by* $(Z(\rho), Z^*(\rho))$ *a pair of total pollution that satisfy* (5) *and* (12). *If* $L = L^*$, *it holds that* $Z(\rho) = Z^*(\rho)$.

*Proof.* Let $L = L^*$. Then, from (5) and (12), we have

$$\frac{[Z(\rho)+\delta Z^*(\rho)]^{\gamma-1}}{1-\beta[Z(\rho)+\delta Z^*(\rho)]^{\gamma-1}Z(\rho)} = \frac{[Z^*(\rho)+\delta Z(\rho)]^{\gamma-1}}{1-\beta[Z^*(\rho)+\delta Z(\rho)]^{\gamma-1}Z^*(\rho)},$$

which can be rewritten as

$$\begin{aligned}&[Z(\rho)+\delta Z^*(\rho)]^{\gamma-1} - [Z^*(\rho)+\delta Z(\rho)]^{\gamma-1}\\ &= \beta[Z(\rho)+\delta Z^*(\rho)]^{\gamma-1}[Z^*(\rho)+\delta Z(\rho)]^{\gamma-1}[Z^*(\rho)-Z(\rho)]. \qquad (13)\end{aligned}$$

As shown in the proof of Proposition 1, if $Z(\rho)$ and $Z^*(\rho)$ satisfy (13), $Z(\rho) = Z^*(\rho)$ must hold. □

LEMMA 2. *Let us denote the relative factor price under the free trade equilibrium with FPE by* $\rho_T$. *If* $L = L^*$, *it holds that* $\rho_A = \rho_A^* = \rho_T$.

*Proof.* In the autarky equilibrium, the relative factor prices $\rho_A$ and $\rho_A^*$ satisfy

$$Z(\rho_A) = \frac{\bar{\theta}\, L}{(1-\bar{\theta})\rho_A} \qquad \text{and} \qquad Z^*(\rho_A^*) = \frac{\bar{\theta}\, L^*}{(1-\bar{\theta})\rho_A^*}. \qquad (14)$$

In the free trade equilibrium, $\rho_T$ satisfies the following condition:

$$Z(\rho_T) + Z^*(\rho_T) = \frac{\bar{\theta}(L+L^*)}{(1-\bar{\theta})\rho_T}. \qquad (15)$$

In light of Proposition 1 and (7), it follows that $\rho_A = \rho_A^*$ if $L = L^*$. Therefore, comparing (14) and (15), we have $\rho_A = \rho_A^* = \rho_T$ if $L = L^*$. □

PROPOSITION 3. *Under the free trade equilibrium with FPE, the equilibrium pollution level in the North (South) is smaller (larger) than the autarky pollution level for* $\forall\delta \in [0, 1]$.

*Proof.* Let $L = \lambda L^*$. From Lemma 1 and 2, we have $Z_T = Z_A = Z_A^* = Z_T^*$ if $\lambda = 1$. Totally differentiating (5), (12) and (11), it follows that

$$\begin{bmatrix} 1-BZ & -A-\rho B & -\delta A \\ 1-B^*Z^* & -\delta A^* & -A^*-\rho B^* \\ (1-\bar{\theta})(Z+Z^*) & (1-\bar{\theta})\rho & (1-\bar{\theta})\rho \end{bmatrix} \begin{bmatrix} d\rho \\ dZ \\ dZ^* \end{bmatrix} = \begin{bmatrix} BL^* \\ 0 \\ \bar{\theta}L^* \end{bmatrix} d\lambda, \qquad (16)$$

where

$$A \equiv \beta(\gamma-1)(Z+\delta Z^*)^{\gamma-2}(\rho Z + L) > 0, \quad B \equiv \beta(Z+\delta Z^*)^{\gamma-1} \in (0, 1/Z),$$

$$A^* \equiv \beta(\gamma-1)(Z^*+\delta Z)^{\gamma-2}(\rho Z^* + L^*) > 0, \quad B^* \equiv \beta(Z^*+\delta Z)^{\gamma-1} \in (0, 1/Z^*).$$

Solving (16), we have[5]

[5] In deriving (17) and (18), we used (5) and (11) to obtain

$$(1-\bar{\theta})(Z+Z^*)B - (1-BZ)\bar{\theta} = \frac{\bar{\theta}(L+L^*)}{\rho}B - \frac{BL}{\rho}\bar{\theta} = \frac{B\bar{\theta}L^*}{\rho}.$$

$$\frac{dZ}{d\lambda} = -\frac{L^*}{\Delta}\left\{(1 - B^*Z^*)[(1-\bar{\theta})\rho B + \bar{\theta}\delta A] + (A^* + \rho B^*)\frac{B\bar{\theta}L^*}{\rho}\right\} < 0, \quad (17)$$

$$\frac{dZ^*}{d\lambda} = \frac{L^*}{\Delta}\left\{(1 - B^*Z^*)[(1-\bar{\theta})\rho B + \bar{\theta}(A + \rho B)] + \delta A^*\frac{B\bar{\theta}L^*}{\rho}\right\} > 0, \quad (18)$$

where

$$\Delta \equiv (1-\bar{\theta})\big\{[\rho(1 - B^*Z^*) + (Z + Z^*)\delta A^*][(1-\delta)A + \rho B] + [\rho(1 - BZ) + (Z + Z^*)(A + \rho B)][(1-\delta)A^* + \rho B^*]\big\} > 0.$$

In light of (17) and (18), it follows that $Z_T < Z_A = Z_A^* < Z_T^*$ if $\lambda > 1$. □

Let us turn to the effect of trade on the total pollution in the world, $Z + Z^*$. From (17), (18) and (12), we have

$$\frac{d(Z + Z^*)}{d\lambda} = \frac{L^*}{\Delta}(1 - B^*Z^*)\bar{\theta}(1-\delta)\frac{AB^* - A^*B}{B^*}. \quad (19)$$

It is clear from (19) that in the case of perfect international spillover of pollution (i.e., $\delta = 1$), the total pollution is independent of $\lambda$. This means that $Z + Z^*$ under autarky is the same as under free trade, as shown by Copeland and Taylor (1995, Proposition 1). For the case of $\delta \in [0, 1)$, the sign of (19) depends on the sign of $AB^* - A^*B$, which can be rewritten as

$$AB^* - A^*B$$
$$= \beta^2(\gamma - 1)[(Z + \delta Z^*)(Z^* + \delta Z)]^{\gamma-2}[(\rho Z + L)(Z^* + \delta Z) - (\rho Z^* + L^*)(Z + \delta Z^*)].$$

In light of (5) and (12), it follows that

$$\rho Z + L - (\rho Z^* + L^*) = \frac{L}{1 - BZ}\left(1 - \frac{B}{B^*}\right).$$

As shown in Proposition 3, $Z < Z^*$ holds if $L > L^*$. This means that both $B < B^*$ and $Z^* + \delta Z > Z + \delta Z^*$ hold. Hence we have $AB^* - A^*B > 0$, that is, $d(Z + Z^*)/d\lambda > 0$ if $\lambda > 1$. To sum up, we have the following proposition:

PROPOSITION 4. *Under the free trade equilibrium with FPE, the total pollution level in the world is larger than the total pollution under autarky for* $\delta \in [0, 1)$. *If* $\delta = 1$, *trade leaves the total pollution unchanged.*

## 4. CONCLUSION

This paper re-examined the North-South trade model developed by Copeland and Taylor (1994, 1995), by allowing for an imperfect international spillover of pollution. Attention is focused on the free trade equilibrium in which factor prices are equalized between countries. Assuming that the government in each country determines its pollution policy so as to maximize the national welfare, the pollution level in each country is obtained as a Nash equilibrium of environmental policy game. Under these assumptions, it is shown that the free-trade equilibrium pollution level is smaller (larger) than the autarky pollution level in the North (South) for any degrees of pollution spillover.

This result was proved in the global pollution case by Copeland and Taylor (1995) and was noted in the local pollution case by Copeland and Taylor (1994) without proof. It is also shown that the total pollution level in the world (i.e., the sum of pollution in the North and the South) under the free trade equilibrium is larger than the total pollution under autarky, except for a case of global pollution, in which the total pollution is unaffected by trade. These results are, of course, consistent with those in Copeland and Taylor (1994, 1995).

## Appendix: Proof of Proposition 2

Given the assumptions that the North is effective-labor abundant and that $\alpha(s)$ is increasing in $s$, the North specializes in effective-labor-intensive goods and the South specializes in pollution-intensive goods if factor prices are not equalized. Let us denote the index of a marginal good in the non-FPE equilibrium by $\bar{s}$. Then, this good is produced at equal cost in both countries, or equivalently, $c(w, \tau; \bar{s}) = c(w^*, \tau^*; \bar{s})$ holds. In light of the production technology (1), this condition is equivalent to

$$\omega \equiv \frac{w}{w^*} = \left(\frac{\tau^*}{\tau}\right)^{\frac{\alpha(\bar{s})}{1-\alpha(\bar{s})}}. \tag{A.1}$$

From (4), the ratio of the pollution prices is

$$\frac{\tau^*}{\tau} = \left(\frac{\delta Z + Z^*}{Z + \delta Z^*}\right)^{\gamma-1} \frac{I^*}{I} = \left[\frac{\delta(Z/Z^*) + 1}{Z/Z^* + \delta}\right]^{\gamma-1} \frac{I^*}{I}. \tag{A.2}$$

Since the North's share of world income equals the share of world spending on Northern goods, $I = (I + I^*) \int_0^{\bar{s}} b(s)ds$ holds. Similarly for the South, $I^* = (I + I^*) \int_{\bar{s}}^1 b(s)ds$ holds. In addition, the aggregate Northern pollution is the sum of pollution generated by the production of Northern outputs, that is,

$$Z = \int_0^{\bar{s}} z(s)ds = \int_0^{\bar{s}} \frac{\alpha(s)p(s)y(s)}{\tau} ds = \int_0^{\bar{s}} \frac{\alpha(s)b(s)(I + I^*)}{\tau} ds = \frac{I \int_0^{\bar{s}} \alpha(s)b(s)ds}{\tau \int_0^{\bar{s}} b(s)ds}.$$

Similarly for the South,

$$Z^* = \frac{I^* \int_{\bar{s}}^1 \alpha(s)b(s)ds}{\tau^* \int_{\bar{s}}^1 b(s)ds}.$$

Therefore,

$$\frac{Z}{Z^*} = \frac{(\tau^*/\tau) \int_0^{\bar{s}} \alpha(s)b(s)ds \int_{\bar{s}}^1 b(s)ds}{(I^*/I) \int_0^{\bar{s}} b(s)ds \int_{\bar{s}}^1 \alpha(s)b(s)ds}.$$

Substituting the above equations into (A.2), it follows that

$$\frac{\tau^*}{\tau} = \left[\frac{\delta(\tau^*/\tau) \int_0^{\bar{s}} \alpha(s)b(s)ds + \int_{\bar{s}}^1 \alpha(s)b(s)ds}{(\tau^*/\tau) \int_0^{\bar{s}} \alpha(s)b(s)ds + \delta \int_{\bar{s}}^1 \alpha(s)b(s)ds}\right]^{\gamma-1} \frac{\int_{\bar{s}}^1 b(s)ds}{\int_0^{\bar{s}} b(s)ds}. \tag{A.3}$$

If $\delta = 0$ or $\delta = 1$, (A.3) is simplified to $\tau^*/\tau = \int_{\bar{s}}^1 b(s)ds \big/ \int_0^{\bar{s}} b(s)ds$. If $0 < \delta < 1$, it can be verified that the right-hand side of (A.3) is monotonically decreasing in $\tau^*/\tau$.

Thus, (A.3) has a unique solution for $\tau^*/\tau$, which depends on $\bar{s}$. We denote it by $\Phi(\bar{s})$, and (A.1) can be rewritten as follows (note that $\Phi(\bar{s}) = \int_{\bar{s}}^1 b(s)ds \big/ \int_0^{\bar{s}} b(s)ds$ if $\delta = 0$ or $\delta = 1$):

$$\omega = \Phi(\bar{s})^{\frac{\alpha(\bar{s})}{1-\alpha(\bar{s})}} \equiv F(\bar{s}). \tag{A.4}$$

That is, North will produce all goods in the interval $[0, \bar{s})$ if (A.4) and $\tau > \tau^*$ hold in equilibrium.

The condition $\tau > \tau^*$ requires that $\Phi(\bar{s}) < 1$ and thus, (A.4) is valid only for $\bar{s} > \hat{s}$, where $\hat{s}$ is implicitly defined by $\Phi(\hat{s}) \equiv 1$. Substituting $\tau = \tau^*$ into (A.3), $\hat{s}$ is shown to satisfy

$$\left[\frac{\delta \int_0^{\hat{s}} \alpha(s)b(s)ds + \int_{\hat{s}}^1 \alpha(s)b(s)ds}{\int_0^{\hat{s}} \alpha(s)b(s)ds + \delta \int_{\hat{s}}^1 \alpha(s)b(s)ds}\right]^{\gamma-1} \frac{\int_{\hat{s}}^1 b(s)ds}{\int_0^{\hat{s}} b(s)ds} = 1. \tag{A.5}$$

Since the left-hand side of (A.5) approaches $\infty$ and 0 as $\hat{s} \to 0$ and 1, respectively, and is shown to be monotonically decreasing in $\hat{s}$, $\hat{s} \in (0, 1)$ exists uniquely.

To determine the marginal good $\bar{s}$ in the non-FPE equilibrium, we obtain another condition that links $\omega$ and $\bar{s}$ by using the relationships $\tau Z = I \int_0^{\bar{s}} \alpha(s)b(s)ds \big/ \int_0^{\bar{s}} b(s)ds$ and $\tau^* Z^* = I^* \int_{\bar{s}}^1 \alpha(s)b(s)ds \big/ \int_{\bar{s}}^1 b(s)ds$ derived above as well as the definition of national income in each country, i.e., $I = wL + \tau Z$ and $I^* = w^*L^* + \tau^* Z^*$. Hence,

$$\omega = \frac{L^*}{L} \frac{\int_0^{\bar{s}} [1 - \alpha(s)]b(s)ds}{\int_{\bar{s}}^1 [1 - \alpha(s)]b(s)ds} \equiv G(\bar{s}). \tag{A.6}$$

It can be verified that $F(s)$ is monotonically decreasing in $s$ for $s \in [\hat{s}, 1]$ and $G(s)$ is monotonically increasing in $s \in [0, 1]$. Thus, we have a marginal good $\bar{s} \in (\hat{s}, 1)$ if and only if $1 > G(\hat{s})$, as shown in Figure A.1, and if this is the case, factor prices are not equalized in the trading equilibrium. Moreover, (A.6) shows that $G(s)$ is increasing in $L^*/L$, which means that as $L^*/L$ rises, there is a point at which $F(s)$ and $G(s)$ intersect at $s = \hat{s}$. At this point, $\omega = 1$ holds, meaning that factor prices just equalize.

Let us define

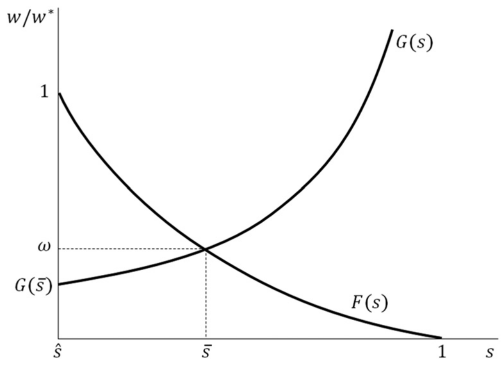


Figure A.1. Determination of $\bar{s}$ in the non-FPE equilibrium

$$\hat{\lambda} \equiv \frac{\int_0^{\hat{s}} [1-\alpha(s)]b(s)ds}{\int_{\hat{s}}^1 [1-\alpha(s)]b(s)ds}. \tag{A.7}$$

From (A.4), (A.6), and (A.7), we have $F(\hat{s}) = G(\hat{s})$ when $\hat{\lambda}L^*/L = 1$. If $\hat{\lambda}L^*/L > 1$, there is no intersection of $F(s)$ and $G(s)$ in $[\hat{s}, 1]$, meaning that we have an FPE equilibrium. By contrast, we have a non-FPE equilibrium for $L > \hat{\lambda}L^*$. □

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