Transboundary Pollution and Welfare Effects of Technology Transfer

Yasuhiro Takarada*

Faculty of Policy Studies,

Nanzan University,

Seto, Aichi 489-0863, Japan

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Abstract

The purpose of this paper is to examine the welfare effects of pollution abatement technology transfer in a two-good two-country model with transboundary pollution. In each country, one industry emits pollution as a joint product of output and the sum of domestic and cross-border pollution decreases productivity of the other industry. Then, we show that technology transfer can benefit the recipient country regardless of the level of cross-border pollution. Moreover, the donor country gains from technology transfer if all pollution is transboundary but it may harm the donor country without cross-border pollution. We demonstrate that the effects of technology transfer depend on the trade pattern as well as cross-border pollution.

Keywords: Environment; Pollution; Technology transfer; Pareto-improving transfer

JEL classification: D62; F18; O39

*Corresponding author: Yasuhiro Takarada. Address: 27 Seirei-cho, Seto, Aichi 489-0863, Japan. Tel.: +81-561-89-2010 (ext. 3541). Fax: +81-561-89-2012. *E-mail address*: ytakara@ps.nanzan-u.ac.jp

1 Introduction

In recent years, there has been growing concern with the effects of economic development on the global environment. For example, we are concerned that a recent increase in green-house gases alters each country's climate and the change may negatively affect agricultural production (e.g., OECD Environmental Outlook, 2001). We recognize that each country should introduce environmental policy to resolve global environmental problems.

This paper examines the effects of pollution abatement technology transfer in a two-good two-country model. In each country, a dirty industry emits pollution as a joint product of output and the sum of domestic and cross-border pollution decreases productivity of a clean industry. The basic structure of our model is based on Copeland and Taylor (1999), Benarroch and Thille (2001), and Unteroberdoerster (2001). Their focus was on the impact of free trade and did not analyze the effects of technology transfer. The transfer of pollution abatement technology is assumed to reduce the emission rate of pollution in a recipient country. The present paper investigates the effects of technology transfer on terms of trade and the amount of pollution. We also explore how technology transfer affects each country's welfare and world welfare.

The analysis of pollution abatement technology transfer is important in the following sense. In many countries, especially in developing countries, the government has difficulty in taking positive measures to deal with environmental degradation because of the lack of funds and pollution abatement technology for preservation and clean-up. Thus, the transfer of pollution abatement technology transfer may be a possible resolution to global environmental problems. Moreover, the third Conference of Parties to the United Nations Framework Convention on Climate Change (COP3) held in Kyoto in 1997 adopted, so-called, the Kyoto Protocol. The protocol includes an important agreement that the targets of reduction in green-house gases (GHGs) in developed countries were explicitly set. The Kyoto Protocol introduces the so-called 'Kyoto mechanisms' as an international system to promote to achieve such commitments. One of the important Kyoto mechanisms is a clean development mechanism (CDM). It allows developed countries (Annex I Party) to acquire from developing countries (non-Annex I Party), as "certified reduction emissions", the emissions reduction resulting from emissions reduction projects in the developing countries.[1] Pollution abatement technology transfer is considered as one of the important measures to utilize CDM.

We derive the following results. First, we show that the transfer of pollution abatement technology increases the price of the polluting good. Second, under no transboundary pollution, technology transfer increases the domestic pollution in the donor country. If all pollution is transboudary, then technology transfer reduces the amount of pollution affecting the donor country under certain conditions. On the other hand, in the recipient country, technology transfer decreases the amount of pollution affecting the recipient country under certain conditions regardless of the level of transboundary pollution. Third, under no transboundary pollution, technology transfer harms the donor country if the donor country imports the polluting good but the donor country benefits from technology transfer if the donor country exports the polluting good and does not emit pollution. On the other hand, under the presence of cross-border pollution, technology transfer can harm or enrich the donor country depending on the trade pattern. Forth, technology transfer enriches the recipient country if the recipient country exports the polluting good regardless of the fraction of transboudary pollution but technology transfer

[1]If emissions reduction projects are implemented between the developed countries, it is called Joint Implementation (JI) instead of CDM. The Kyoto Protocol permits JI as one of the Kyoto mechanisms.

may harm the recipient country if the recipient country imports the polluting good. Finally, we demonstrate the sufficient conditions for Pareto improvement.

There has been a few studies on the effects of technology transfer on the environment. Buchholz and Konrad (1994) and Stranlund (1996) examined the global environmental problem by using a game-theoretic approach. They used a one-good model because their focus was on the strategic behavior of countries toward pollution abatement technology. Then, they cannot deal with the terms-of-trade effect on pollution which works in the present model. In other words, a one-good model cannot investigate the inter-industry interaction caused by pollution. Thus, a change in pollution might be underestimated in their model.

There exist sharp differences on the welfare effects of technology transfer between Itoh and Tawada (2003) and the present paper although the basic structure of both models is based on Copeland and Taylor (1999) and technology transfer is the same type (i.e., technology transfer reduces the emission rate in the recipient country). Under local pollution, technology transfer never benefits the donor country in their model but technology transfer can enrich the donor country in the present model. More importantly, under cross-border pollution, Itoh and Tawada (2003) demonstrated that both the donor and the recipient is better off by the pollution abatement technology transfer but we derive that technology transfer may impoverish the recipient country as well as the donor country.

We explain that such contradiction arises because of differences in the terms-of-trade effect and international interaction caused by transboundary pollution. Since the trade pattern in each country is determined by the assumption on pollution in Itoh and Tawada (2003), they cannot deal with some trade patterns which can be examined in this paper. In the present model, the terms-of-trade effect has impact opposite to their model. Since their analysis is limited to special trade patterns, they may have overestimated the terms-of-trade effect. International interaction caused by transboundary pollution is also important. In this paper, both the donor and the recipient produce the clean good and the polluting good. Then, there are interactions not only between the industries due to pollution externality but also between the countries through cross-border pollution. On the other hand, in Itoh and Tawada (2003), at least one of the donor and the recipient completely specializes because their model behaves like the Ricardian model. Because of this feature, pollution abatement technology transfer has *no* international interaction which works in the present model. Hence, they may have underestimated the impact of cross-border pollution. We show the conditions for welfare improvement by technology transfer in a model with incomplete specialization. This paper adds a new value to this field of research.

The remainder of this paper is organized as follows. We develop a model in Section 2. We examine the effects of technology transfer on terms of trade and pollution in Section 3. Section 4 explores the welfare effects of technology transfer. Finally, we provide concluding remarks.

2 The Model

We develop a two-country general equilibrium model to investigate the welfare effects of the transfer of pollution abatement technology under cross-border pollution. Country α is the donor and country β is the recipient. In each country, there are two industries denoted M and A. Industry M is a dirty industry that emits pollution as a joint product of output. Pollution generated by industry M degrades the natural environment useful to industry A and then decreases productivity of industry A. The markets of goods and factors of production are competitive in both countries. All goods are assumed to be produced in both countries.

Consider the production structure of the donor country.[2] Production function of M is $Q_M^\alpha = F_M^\alpha(v_M^\alpha)$, where v_M^α is the vector of factors employed in industry M. $F_M^\alpha(\cdot)$ is increasing, concave, and linearly homogeneous in inputs. We assume that one unit of M generates λ^α units of pollution. It denotes the degree of dirtiness of the industry. The level of pollution, d^α, caused by the domestic output of M is given by $d^\alpha = \lambda^\alpha Q_M^\alpha$.

Under the presence of transboundary pollution, the total level of pollution, D^α, affecting the donor country is given by

$$D^\alpha = d^\alpha + b^\alpha d^\beta, \tag{1}$$

where $d^\beta = \lambda^\beta Q_M^\beta$ is the level of pollution caused by the domestic output of M in the recipient country and the parameter, b^α, indicates the fraction of transboundary pollution affecting the donor country ($0 \leq b^\alpha \leq 1$). With $b^\alpha = 0$, there is no cross-border pollution, whereas with $b^\alpha = 1$ all pollution is transboundary.

Let us consider industry A. Production function of A is given by $Q_A^\alpha = m^\alpha(D^\alpha)F_A^\alpha(v_A^\alpha)$. v_A^α is the vector of factors used in industry A. $F_A^\alpha(\cdot)$ is increasing, concave, and linearly homogeneous in inputs. $m^\alpha = m^\alpha(D^\alpha)$ is the degree of pollution externality ($0 < m^\alpha(D^\alpha) \leq 1$ and $m^{\alpha\prime}(D^\alpha) < 0$). We assume that a representative firm in industry A treats the amount of pollution, D^α, as exogenously given.

We define the gross domestic product (GDP) function as follows:

$$\widetilde{G}^\alpha(p, m^\alpha, v^\alpha) = \max_v \left\{ pF_M^\alpha(v_M^\alpha) + m^\alpha(D^\alpha)F_A^\alpha(v_A^\alpha) \mid v_M^\alpha + v_A^\alpha = v^\alpha \right\}, \tag{2}$$

where p and v^α denote the world relative price of M and the factor endowment vector of the donor country, respectively. It is linearly homogeneous in p and m^α (e.g., Helpman, 1984, p.334).

[2] The production structure of the recipient country is similar to that of the donor country. In this paper, we allow differences in production technologies and preferences between the donor and the recipient.

Let us define the following function:

$$\widetilde{R}^{\alpha}(q^{\alpha}, v^{\alpha}) = \max_{v} \left\{ q^{\alpha} F_M^{\alpha}(v_M^{\alpha}) + F_A^{\alpha}(v_A^{\alpha}) \mid v_M^{\alpha} + v_A^{\alpha} = v^{\alpha} \right\}, \tag{3}$$

where $q^{\alpha} \equiv \frac{p}{m^{\alpha}(D^{\alpha})}$. The value of $\widetilde{R}^{\alpha}(\cdot)$ is the 'virtual' national income of the donor country since it denotes the national income under no production externality and the 'virtual' price, q^{α}. We define the 'virtual' national income and price to describe equilibrium by utilizing the traditional GDP function. $\widetilde{R}^{\alpha}(\cdot)$ behaves like the standard GDP function with constant returns to scale technologies.

By using the virtual national income, we can rewrite the GDP function as $\widetilde{G}^{\alpha}(p, m^{\alpha}, v^{\alpha}) = m^{\alpha}(D^{\alpha})\widetilde{R}^{\alpha}(q^{\alpha}, v^{\alpha})$. It has the following property: $\widetilde{G}_p^{\alpha} = \widetilde{R}_q^{\alpha} = Q_M^{\alpha}$ where a subscript indicates differentiation, i.e., $\widetilde{G}_p^{\alpha} \equiv \frac{\partial \widetilde{G}^{\alpha}(p, m^{\alpha}, v^{\alpha})}{\partial p}$ (see Appendix A). Henceforth, we delete the fixed factor endowment vector, i.e., $G^{\alpha}(p, m^{\alpha}) \equiv \widetilde{G}^{\alpha}(p, m^{\alpha}, v^{\alpha})$ and $R^{\alpha}(q^{\alpha}) \equiv \widetilde{R}^{\alpha}(q^{\alpha}, v^{\alpha})$. Then, $G^{\alpha}(p, m^{\alpha}) = m^{\alpha}(D^{\alpha})R^{\alpha}(q^{\alpha})$. We should notice that the GDP function, $G^{\alpha}(p, m^{\alpha})$, includes information of pollution externality.

The equilibrium of the world economy is described by the system of equations:[3]

$$E^{\alpha}(p, u^{\alpha}) = G^{\alpha}(p, m^{\alpha}), \tag{4}$$

$$D^{\alpha} = \lambda^{\alpha} R_q^{\alpha}(q^{\alpha}) + b^{\alpha}\lambda^{\beta} R_q^{\beta}(q^{\beta}), \tag{5}$$

$$E^{\beta}(p, u^{\beta}) = G^{\beta}(p, m^{\beta}), \tag{6}$$

$$D^{\beta} = \lambda^{\beta} R_q^{\beta}(q^{\beta}) + b^{\beta}\lambda^{\alpha} R_q^{\alpha}(q^{\alpha}), \tag{7}$$

$$E_p^{\alpha}(p, u^{\alpha}) + E_p^{\beta}(p, u^{\beta}) - R_q^{\alpha}(q^{\alpha}) - R_q^{\beta}(q^{\beta}) = 0, \tag{8}$$

[3]The equilibrium in our model essentially replicates the steady state in Copeland and Taylor (1999) and Unteroberdoerster (2001) that modeled pollution as a stock in a dynamic model.

where $E^j(p, u^j)$ is the expenditure function with the level of utility, u^j $(j = \alpha, \beta)$. Equations (4) and (6) are the budget constraint of the donor and the recipient, respectively. Equations (5) and (7) indicate the endogenous level of pollution (i.e., domestic pollution plus transboundary pollution) in the donor and the recipient, respectively. Equation (8) is the market-clearing condition for the polluting good, M. The world market for A also clears by Walras' Law.

3 Terms of Trade and Global Pollution

In this section, we investigate the impact of pollution abatement technology transfer on terms of trade and pollution. They are essential to the welfare effects of technology transfer. If the donor country transfers pollution abatement technology to the recipient country, then the emission rate of the recipient country, λ^β, decreases. We assume that pollution abatement technology is transferred without cost in order to highlight the impact of technology transfer. All goods are assumed to be normal in consumption in both countries, i.e., $pE^\alpha_{pu} > 0$ and $pE^\beta_{pu} > 0$.

First, we consider changes in the terms of trade. Totally differentiating equations (4)-(8) and choosing $E^j_u \equiv 1$, we obtain

$$\Delta \left(\frac{dp}{d\lambda^\beta} \right) = R^\beta_q \left[\frac{R^\beta_{qq} p m^{\beta\prime}}{(m^\beta)^2} - E^\beta_{pu} r^\beta \right] \left[1 + (1 - b^2) \frac{\lambda^\alpha R^\alpha_{qq} p m^{\alpha\prime}}{(m^\alpha)^2} \right] + b R^\beta_q \left[\frac{R^\alpha_{qq} p m^{\alpha\prime}}{(m^\alpha)^2} - E^\alpha_{pu} r^\alpha \right], \quad (9)$$

where $b \equiv b^\alpha = b^\beta$.[4] Δ represents the Jacobian determinant of the system (4)-(8). Under certain conditions on the interaction between the emission rate and pollution, Δ is positive if the equilibrium is Walrasian stable (see Appendix B). We assume $\Delta > 0$ throughout this paper.

Equation (9) shows that pollution abatement technology transfer unambiguously increases the price of the polluting good. Note that this effect of technology transfer is independent of the

[4]The essence of our results remains valid even if we assume $b^\alpha \neq b^\beta$.

marginal propensities to consume goods and the emission rate in each country. From Appendix B, $1+\frac{\lambda^j R_{qq}^j p m^{j\prime}}{(m^j)^2} = (1+\epsilon_q^j \epsilon_D^j) - bd^i \epsilon_q^j \frac{m^{j\prime}}{m^j}$ $(i \neq j)$ is positive. Then, $1+(1-b^2)\frac{\lambda^\alpha R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2} > 0$ because $1-b^2$ is smaller than one. We can rewrite r^α and r^β as $r^\alpha = -\frac{Q_A^\alpha m^{\alpha\prime}}{m^\alpha} > 0$ and $r^\beta = -\frac{Q_A^\beta m^{\beta\prime}}{m^\beta} > 0$, respectively, because $pR_q^j - m^j R^j = -Q_A^j < 0$. Hence, the right hand side of equation (9) is negative. We derive this result regardless of the fraction of transboundary pollution.

Then, we obtain the following proposition.

Proposition 1. *The transfer of pollution abatement technology increases the price of the polluting good.*

Technology transfer increases the price of the polluting good under incomplete specialization in both countries. On the other hand, if the recipient country produces the clean good only (i.e., $R_q^\beta = 0$), technology transfer is meaningless and the price of the polluting good does not change. This paper extends the result of the terms-of-trade effect in Itoh and Tawada (2003) in which at least one country completely specializes.

Second, we examine the effects of technology transfer on pollution affecting each country. Intuitively, we expect that a decrease in the emission rate in country β reduces the amount of pollution in both countries if pollution is transboundary. However, technology transfer does not always have such impact.

Totally differentiating equations (4)-(8), we obtain

$$\Delta\left(\frac{dD^\alpha}{d\lambda^\beta}\right) = -bR_q^\beta Z + R_q^\beta\left[\frac{R_{qq}^\beta p m^{\beta\prime}}{(m^\beta)^2} - E_{pu}^\beta r^\beta\right](M_1 - bM_2), \tag{10}$$

$$\Delta\left(\frac{dD^\beta}{d\lambda^\beta}\right) = -R_q^\beta Z\left[1+(1-b^2)\frac{\lambda^\alpha R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2}\right] - R_q^\beta\left[\frac{R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2} - E_{pu}^\alpha r^\alpha\right](M_1 - bM_2), \tag{11}$$

where $Z \equiv z_{pp} - (E_p^\beta - R_q^\beta)(E_{pu}^\beta - E_{pu}^\alpha)$ and $z_{pp} \equiv E_{pp}^\alpha + E_{pp}^\beta - \frac{R_{qq}^\alpha}{m^\alpha} - \frac{R_{qq}^\beta}{m^\beta} < 0$. From Appendix B, we can rewrite $M_1 - bM_2$ as $M_1 - bM_2 = (1 - b^2)\frac{\lambda^\alpha R_{qq}^\alpha}{m^\alpha} > 0$.

From equation (10), the impact of pollution abatement technology transfer on D^α is ambiguous in general. We will consider two cases according to the fraction of cross-border pollution. Under no transboundary pollution, $b = 0$, technology transfer unambiguously increases pollution in the donor country. Recall that the price of the polluting good increases after technology transfer. The output of the polluting good increases and therefore pollution expands in the donor country. Technology transfer deteriorates the natural environment useful to the clean good in the donor country under the absence of transboundary pollution.

Suppose that all pollution is transboudary, $b = 1$. Then, $M_1 - bM_2 = 0$. Technology transfer reduces the amount of pollution affecting the donor country if $Z < 0$.[5] Z is negative if either of the following conditions is satisfied: (i) the equilibrium without pollution externality (i.e., $b = 0$, $\lambda^\alpha = \lambda^\beta = 0$, and $m^\alpha = m^\beta = 1$) is Walrasian stable; (ii) the recipient country imports (exports) the polluting good and the marginal propensity to consume it in the recipient country is larger (smaller) than that in the donor country (i.e., $(E_p^\beta - R_q^\beta)(E_{pu}^\beta - E_{pu}^\alpha) \geq 0$).[6]

We can explain the intuition of this result as follows. Technology transfer directly reduces transboundary pollution from the recipient to the donor under the fixed output of the polluting good in the recipient. On the other hand, since technology transfer increases the price of the polluting good (Proposition 1), it indirectly has a negative impact on the environment in the donor country through an increase in the output of the polluting good in both countries. However, the former impact of cross-border pollution dominates the later effect when all pollution is

[5]We can derive a similar result if we assume $\lambda^\alpha = 0$ instead of $b = 1$.

[6]Since there are differences in the emission rate, production technologies, and preference between the donor and the recipient, various trade patterns can take place in the present model.

transboundary. Hence, pollution abatement technology transfer can improve the environment if transboundary pollution is sufficiently large.

From equation (11), technology transfer decreases the amount of pollution affecting the recipient country under $Z < 0$. Notice that this result holds with and without transboundary pollution. The reasoning is similar to the case of the donor country. The transfer of pollution abatement technology can lower the amount of pollution although the price of the polluting good increases after the transfer.

Summing up, we obtain the following proposition.

Proposition 2. *Technology transfer changes the amount of pollution affecting the donor country and the recipient country as follows. (i) The case of the donor country: (a) under no transboundary pollution, technology transfer increases the domestic pollution; (b) if all pollution is transboudary, then technology transfer reduces the amount of pollution affecting the donor country under $Z < 0$. (ii) The case of the recipient country: technology transfer decreases the amount of pollution affecting the recipient country under $Z < 0$ regardless of the level of transboundary pollution.*

We show that pollution abatement technology transfer may paradoxically increase the amount of pollution. On the contrary, in Itoh and Tawada (2003), pollution abatement technology transfer will reduce pollution. We can explain why such contradiction occurs as follows. In their model, preference is assumed to be identical between the donor and the recipient. This implies $Z < 0$ because of $E^{\alpha}_{pu} = E^{\beta}_{pu}$. From Proposition 2, technology transfer decreases pollution affecting each country except case (i)-(a).

The exception occurs because of the difference in production pattern. In Itoh and Tawada

(2003), there are two production patterns in the recipient country under local pollution: (i) complete specialization in the polluting good; (ii) incomplete specialization. Under local pollution, pollution in the donor country can increase if the domestic output of the polluting good increases through a price change. Since the recipient country completely specializes in the polluting good in the former case, improvement in the environment by technology transfer has no effect on the supply of the clean good. Namely, there is no terms-of-trade effect. Therefore, the domestic pollution in the donor country never changes. In the latter case, the donor country produces the clean good only. Thus, there is no pollution emission in the donor country. Since Itoh and Tawada (2003) examined technology transfer in the context of special production patterns, they may have overestimated the reduction of pollution by technology transfer.

Finally, we examine changes in the sum of pollution affecting the donor and the recipient (global pollution), i.e., $D^\alpha + D^\beta = (1+b)(d^\alpha + d^\beta)$. In other words, how technology transfer changes the sum of each country's emission, $d^\alpha + d^\beta$ (because b is assumed to be constant in this paper). From equations (10) and (11), we derive

$$\begin{aligned}\Delta\left(\frac{dD^\alpha}{d\lambda^\beta} + \frac{dD^\beta}{d\lambda^\beta}\right) &= R_q^\beta(M_1 - bM_2)\left[\frac{R_{qq}^\beta p m^{\beta\prime}}{(m^\beta)^2} - \frac{R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2} - E_{pu}^\beta r^\beta + E_{pu}^\alpha r^\alpha\right] \\ &\quad - R_q^\beta Z\left[1 + b + (1-b^2)\frac{\lambda^\alpha R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2}\right]. \qquad (12)\end{aligned}$$

This analysis has important implication for resolution of the global warming problem by utilizing CDM. In the present model, we can interpret pollution as GHGs. The donor country has an incentive to transfer pollution abatement technology to acquire "certified reduction emissions" if the transfer can decrease the sum of each country's emission. It is straightforward from Proposition 2 that technology transfer necessarily decreases the sum of each country's pollution $(d^\alpha + d^\beta)$ if all pollution is transboundary $(b = 1)$ and $Z < 0$. On the other hand, from

Proposition 2, under $b = 0$ and $Z < 0$, technology transfer increases the domestic pollution in the donor country whereas it lowers that in the recipient country. It is not clear that technology transfer reduces the sum of the two countries' pollution. Thus, we can conclude that an incentive for technology transfer depends on the degree of cross-border pollution.

Using a game-theoretic approach, Buchholz and Konrad (1994) and Stranlund (1996) examined the global environmental problem. Since their focus was on the strategic behavior of countries toward pollution abatement technology, they used a one-good model. Therefore, they cannot deal with the terms-of-trade effect on pollution. A change in pollution might be underestimated in their model. Itoh and Tawada (2003) did not clarify how the global pollution changes as a result of technology transfer.

4 Welfare Effects of Technology Transfer

4.1 The donor country

We examine the welfare effect of pollution abatement technology transfer in the donor country. Totally differentiating equations (4)-(8), we obtain

$$\begin{aligned} \Delta\left(\frac{du^\alpha}{d\lambda^\beta}\right) &= R_q^\beta(E_p^\alpha - R_q^\alpha)\left[1 + (1-b^2)\frac{\lambda^\alpha R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2}\right]\left[E_{pu}^\beta r^\beta - \frac{R_{qq}^\beta p m^{\beta\prime}}{(m^\beta)^2}\right] \\ &\quad + R_q^\beta r^\alpha(M_1 - bM_2)\left[E_{pu}^\beta r^\beta - \frac{R_{qq}^\beta p m^{\beta\prime}}{(m^\beta)^2}\right] + bR_q^\beta z_{pp} r^\alpha \\ &\quad + R_q^\beta b(E_p^\alpha - R_q^\alpha)\left[E_{pu}^\beta r^\alpha - \frac{R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2}\right]. \end{aligned} \tag{13}$$

It is convenient for considering two cases according to the fraction of cross-border pollution.

First, we explore the case of no transboundary pollution ($b = 0$). Under $b = 0$, equation (13) is rewritten as

$$\Delta \left(\frac{du^{\alpha}}{d\lambda^{\beta}} \right) = R_q^{\beta} \left[E_{pu}^{\beta} r^{\beta} - \frac{R_{qq}^{\beta} p m^{\beta \prime}}{(m^{\beta})^2} \right] \left\{ \left[1 + \frac{\lambda^{\alpha} R_{qq}^{\alpha} p m^{\alpha \prime}}{(m^{\alpha})^2} \right] (E_p^{\alpha} - R_q^{\alpha}) + M_1 r^{\alpha} \right\}. \tag{14}$$

We show that the donor country suffers from technology transfer when it imports the polluting good ($E_p^{\alpha} - R_q^{\alpha} \geq 0$).[7] On the other hand, the effect of pollution abatement technology transfer is ambiguous if the donor country exports the polluting good ($E_p^{\alpha} - R_q^{\alpha} < 0$). Especially, technology transfer enriches the donor country if there is no domestic pollution in the donor country ($\lambda^{\alpha} = 0$). We derive $D^{\alpha} = 0$, $m^{\alpha} = 0$, and $m^{\alpha \prime} = 0$ if $\lambda^{\alpha} = 0$. Then, the right hand side of equation (14) is negative.

Then, we obtain the following proposition.

Proposition 3. *Suppose that there is no transboundary pollution. Then, (i) technology transfer harms the donor country if the donor country imports the polluting good but (ii) the donor country benefits from technology transfer if the donor country exports the polluting good and does not emit pollution.*

The result can be explained as follows. Technology transfer increases the relative price of the polluting good (Proposition 1). Moreover, technology transfer increases the domestic pollution in the donor country (Proposition 2), which will cause productivity losses. Both the former and the latter effects deteriorates welfare because the price change is deterioration in terms of trade under $E_p^{\alpha} - R_q^{\alpha} \geq 0$. On the other hand, in the case of $E_p^{\alpha} - R_q^{\alpha} < 0$, the price change implies improvement in terms of trade. The smaller λ^{α} is the smaller productivity losses are. Then, the terms-of-trade effect can outweigh productivity losses if λ^{α} is near zero.

[7] Recall that the recipient country is assumed to produce the polluting good ($R_q^{\beta} > 0$). Otherwise, technology transfer has no effect on welfare.

Second, we investigate the case of cross-border pollution ($b > 0$). From equation (13), the welfare effect of technology transfer is ambiguous in general. Consider the case in which the donor imports the polluting good ($E_p^\alpha - R_q^\alpha \geq 0$). Then, technology transfer can harm the donor country if the fraction of transboundary pollution, b, is sufficiently small. The right hand side of equation (13) can be positive under sufficiently small b.

On the other hand, we consider the case in which the donor country exports the polluting good ($E_p^\alpha - R_q^\alpha < 0$). Then, the donor country benefits from technology transfer if all pollution is transboundary ($b = 1$) or the donor country does not emit pollution ($\lambda^\alpha = 0$). The signs of the first and the last two terms of equation (13) are negative. In the second term, we already know that $M_1 - bM_2$ is zero under $b = 1$ or $\lambda^\alpha = 0$. Hence, the right hand side of equation (13) is negative.

Summing up, we obtain the following proposition.

Proposition 4. *Suppose that there is cross-border pollution. Then, (i) in the case in which the donor country imports the polluting good, technology transfer can harm the donor country if the fraction of transboundary pollution between the countries is sufficiently small. (ii) In the case in which the donor country exports the polluting good, technology transfer enriches the donor country if (a) all pollution is transboundary or (b) the donor country does not emit pollution.*

Intuition of the result is the following. A decrease in pollution affecting the donor country is likely to be small under small b (Proposition 2). The donor country enjoys small productivity gains. When the donor country imports the polluting good, terms of trade deteriorates in the donor country (Proposition 1). The latter effect can outweigh the former effect. Thus, the donor country can suffer from technology transfer even if pollution decreases. On the other hand, a decrease in pollution affecting the donor is large when (a) $b = 1$. The price change is in favor of the donor country when it exports the polluting good. Thus, the donor country benefits from technology transfer. Under (b) $\lambda^\alpha = 0$, a decrease in transboundary pollution from the recipient and improvement in terms of trade determine the welfare result.

4.2 The recipient country

Totally differentiating equations (4)-(8), we obtain

$$\begin{aligned}
\Delta \left(\frac{du^\beta}{d\lambda^\beta} \right) &= R_q^\beta r^\beta \left[1 + (1 - b^2) \frac{\lambda^\alpha R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2} \right] \left[z_{pp} + E_{pu}^\alpha (E_p^\beta - R_q^\beta) \right] \\
&\quad + R_q^\beta r^\beta (M_1 - b M_2) \left[\frac{R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2} - E_{pu}^\alpha r^\alpha \right] + b R_q^\beta E_{pu}^\alpha r^\alpha (E_p^\beta - R_q^\beta) \\
&\quad - b R_q^\beta (E_p^\beta - R_q^\beta) \frac{R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2} \left[1 - b \frac{\lambda^\alpha R_{qq}^\beta p m^{\beta\prime}}{(m^\beta)^2} \right] \\
&\quad - R_q^\beta (E_p^\beta - R_q^\beta) \frac{R_{qq}^\beta p m^{\beta\prime}}{(m^\beta)^2} \left[1 + \frac{\lambda^\alpha R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2} \right]. \qquad (15)
\end{aligned}$$

We will consider two cases according to the trade pattern in order to clarify the impact of technology transfer.

First, we examine the case in which the recipient country exports the polluting good ($E_p^\beta - R_q^\beta \leq 0$). Under $E_p^\beta - R_q^\beta \leq 0$, the right hand side of equation (15) is negative. Thus, the recipient country unambiguously benefits from technology transfer. Notice that we derive this result regardless of the fraction of transboudary pollution, b.

Second, let us assume that the recipient country imports the polluting good ($E_p^\beta - R_q^\beta > 0$). We can rewrite equation (15) as

$$\begin{aligned}
\Delta \left(\frac{du^\beta}{d\lambda^\beta} \right) &= R_q^\beta r^\beta z_{pp} \left[1 + (1 - b^2) \frac{\lambda^\alpha R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2} \right] - R_q^\beta (1 - b^2)(E_p^\beta - R_q^\beta) \frac{\lambda^\alpha R_{qq}^\alpha R_{qq}^\beta p^2 m^{\alpha\prime} m^{\beta\prime}}{(m^\alpha)^2 (m^\beta)^2} \\
&\quad + R_q^\beta E_{pu}^\alpha (E_p^\beta - R_q^\beta)(b r^\alpha + r^\beta) - R_q^\beta (E_p^\beta - R_q^\beta) \left[\frac{b R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2} + \frac{R_{qq}^\beta p m^{\beta\prime}}{(m^\beta)^2} \right]
\end{aligned}$$

$$
+R_q^\beta E_{pu}^\alpha r^\beta (1-b^2)(E_p^\beta - R_q^\beta)\frac{\lambda^\alpha R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2}
$$
$$
+R_q^\beta r^\beta (M_1 - bM_2)\left[\frac{R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2} - E_{pu}^\alpha r^\alpha\right]. \quad (16)
$$

The welfare effect of technology transfer is ambiguous in general. Technology transfer can enrich or harm the recipient country. We know that the third and the forth terms in the right hand side are positive but the other terms are negative. Then, the right hand side of equation (16) may be positive.

Then, we obtain the following proposition.

Proposition 5. *Technology transfer enriches the recipient country if the recipient country exports the polluting good but technology transfer may harm the recipient country if the recipient country imports the polluting good, regardless of the fraction of transboudary pollution.*

We can explain the intuition of the result as follows. In the case in which the recipient country exports the polluting good, the terms-of-trade effect is in favor of the recipient country (Proposition 1). Moreover, technology transfer decreases pollution under certain conditions but it may increase pollution if the conditions are not satisfied (Proposition 2). The recipient country may suffer from productivity losses. The former terms-of-trade effect dominates the latter effect, which holds regardless of the fraction of transboundary pollution. Hence, the recipient country benefits from technology transfer. On the other hand, the terms of trade deteriorates after technology transfer if the recipient country imports the polluting good. In this case, welfare enrichment arises if productivity gains outweigh the terms-of-trade effect.

Finally, let us investigate a possibility of voluntary reduction in the emission rate instead of technology transfer. This analysis can be done by interpreting the welfare result of the recipient in a different way. From Proposition 5, a country is likely to adopt advanced pollution abatement technology to reduce pollution if it exports the polluting good. On the other hand, a country may not voluntarily utilize the advanced technology if it imports the polluting good. The result is dependent on the trade pattern. The reason is the terms-of-trade effect which has impact similar to the case of technology transfer. Our result implies that a country which produces a large amount of the polluting good to export it tends to introduce the pollution-reducing technology voluntarily.

4.3 The world welfare

We investigate the effect of technology transfer on the world welfare, i.e., the sum of the two countries' welfare. From equations (13) and (15), we derive

$$\begin{aligned}\Delta\left(\frac{du^\alpha}{d\lambda^\beta}+\frac{du^\beta}{d\lambda^\beta}\right) &= R_q^\beta(M_1-bM_2)\left[r^\alpha r^\beta(E_{pu}^\beta-E_{pu}^\alpha)-r^\alpha\frac{R_{qq}^\beta pm^{\beta\prime}}{(m^\beta)^2}+r^\beta\frac{R_{qq}^\alpha pm^{\alpha\prime}}{(m^\alpha)^2}\right] \\ &+R_q^\beta r^\beta\left[z_{pp}-E_{pu}^\alpha(E_p^\alpha-R_q^\alpha)\right]\left[1+(1-b^2)\frac{\lambda^\alpha R_{qq}^\alpha pm^{\alpha\prime}}{(m^\alpha)^2}\right] \\ &+R_q^\beta(E_p^\alpha-R_q^\alpha)\left[br^\alpha(E_{pu}^\beta-E_{pu}^\alpha)+r^\beta E_{pu}^\beta\right]+bR_q^\beta z_{pp}r^\alpha \\ &+R_q^\beta r^\beta E_{pu}^\beta(1-b^2)(E_p^\alpha-R_q^\alpha)\frac{\lambda^\alpha R_{qq}^\alpha pm^{\alpha\prime}}{(m^\alpha)^2}. \end{aligned} \tag{17}$$

It is convenient for considering two cases according to the fraction of cross-border pollution and the emission rate.

First, we examine the case in which all pollution is transboundary ($b = 1$). Technology transfer improves the world welfare if the donor country imports the polluting good ($E_p^\alpha - R_q^\alpha > 0$) and the marginal propensity to consume the polluting good in the donor country is sufficiently larger than that in the recipient country. Recall that $M_1 - bM_2$ is zero under $b = 1$. $r^\alpha(E_{pu}^\beta - E_{pu}^\alpha) + r^\beta E_{pu}^\beta$ in the third right hand side term is negative if E_{pu}^α is sufficiently larger than E_{pu}^β. Thus, the right hand side of equation (17) is negative under the conditions.

We can explain the result as follows. Z is negative under the conditions (i.e., $E_p^\alpha - R_q^\alpha > 0$ and $E_{pu}^\beta - E_{pu}^\alpha < 0$). From Proposition 2, technology transfer reduces the amount of pollution affecting each country. Then, there are productivity gains in both countries. From Proposition 5, the recipient country benefits from technology transfer. The welfare of the donor country may improve or deteriorate by technology transfer (Proposition 4). The welfare improvement in the recipient can outweigh the welfare change in the donor under the conditions.

Second, we explore the case in which the donor country does not emit pollution ($\lambda^\alpha = 0$). Technology transfer improves the world welfare if the donor country imports the polluting good ($E_p^\alpha - R_q^\alpha > 0$) and the marginal propensity to consume the polluting good in the donor country is sufficiently larger than that in the recipient country ($br^\alpha(E_{pu}^\beta - E_{pu}^\alpha) + r^\beta E_{pu}^\beta < 0$). Recall that $M_1 - bM_2 = 0$ under $\lambda^\alpha = 0$. Then, the right hand side of equation (17) is negative under the conditions. The reason is similar to the above case.

Summing up, we obtain the following proposition.

Proposition 6. *Suppose that the donor country imports the polluting good and the marginal propensity to consume the polluting good in the donor country is sufficiently larger than that in the recipient country. Then, technology transfer improves the world welfare if (i) all pollution is transboundary or (ii) the donor country does not emit pollution.*

We will compare the results of this paper with the existing literature. There exist sharp differences on the welfare effects of technology transfer between Itoh and Tawada (2003) and the present paper although the basic structure of both models is based on Copeland and Taylor (1999) and technology transfer is the same type (i.e., technology transfer reduces the emission rate in the recipient country). Under local pollution, technology transfer has no impact on the welfare of the recipient country and never benefits the donor country in their model but technology transfer can enrich the donor country and may harm the recipient country in the present model. More importantly, under cross-border pollution, Itoh and Tawada (2003) demonstrated that both the donor and the recipient can be better off by the pollution abatement technology transfer and technology transfer never harms the donor country and the recipient country. However, we derive that technology transfer may impoverish the recipient country as well as the donor country. These differences imply that they may have underestimated the effects of technology transfer.

We can consider that such inconsistency arises because of three factors. The first factor is asymmetry of the present model. Itoh and Tawada (2003) assumed that the donor country is identical to the recipient country except for the pollution function. The emission rate in the recipient is assumed to be larger than that in the donor. On the other hand, in the present model, the donor and the recipient are asymmetric. This causes the following essential factors.

The second factor is differences in the terms-of-trade effect. Since the trade pattern in each country is determined by the assumption on pollution in Itoh and Tawada (2003), they cannot deal with trade patterns such as (ii) in Proposition 3, (i) in Proposition 4, and Proposition 5. For example, under the presence of transboundary pollution, the donor country exports the polluting good because it has a comparative advantage in the production of the polluting good in their framework. Then, the terms-of-trade effect caused by technology transfer is in favor of the donor country. On the contrary, the present model can examine not only the case in their model but also the case in which the donor country imports the polluting good. In the latter case, the terms-of-trade effect has impact opposite to their model. The terms-of-trade effect may offset productivity gains, which never occurs in their model. Since their analysis was limited to special trade patterns, they were unable to estimate the terms-of-trade effect appropriately.

The third factor is international interaction caused by transboundary pollution. In this paper, both the donor and the recipient produce the clean good and the polluting good. Then, there are interactions not only between the industries due to pollution externality but also between the countries through cross-border pollution. On the other hand, in Itoh and Tawada (2003), at least one of the donor and the recipient completely specializes because their model behaves like the Ricardian model. Because of this feature, pollution abatement technology transfer has *no* international interaction which works in the present model. For example, in Itoh and Tawada (2003) under cross-border pollution, the recipient country produces the polluting good only if the donor country completely specializes in the polluting good. Although technology transfer reduces the amount of pollution generated in the recipient country, the donor country is not affected by cross-border pollution. Hence, they may have underestimated the impact of cross-border pollution.

5 Concluding Remarks

This paper examines the effects of pollution abatement technology transfer in a two-good two-country model. In each country, a dirty industry emits pollution as a joint product of output and the sum of domestic and cross-border pollution decreases productivity of a clean industry. The transfer of pollution abatement technology reduces the emission rate of pollution in a recipient country. The present paper investigates the effects of technology transfer on terms of trade and the amount of pollution affecting each country. We also explore how technology transfer affects each country's welfare and world welfare.

In the present model, we demonstrate that technology transfer is not always welfare improving for the donor and the recipient even if pollution is transboundary. On the contrary, Itoh and Tawada (2003) showed that both the donor and the recipient are better off by the pollution abatement technology transfer if pollution in one of the two countries is global but welfare of the donor country may fall if pollution in each country is local. Although the basic structure of both models is based on Copeland and Taylor (1999) and technology transfer is the same type (i.e., technology transfer reduces the emission rate in the recipient country), there are such sharp differences. Both countries produce the polluting good and the clean good in the present model. However, in Itoh and Tawada (2003), at least one country completely specializes. This difference in production causes such inconsistency. This paper, together with Itoh and Tawada (2003), implies that technology transfer is effective to solve global environmental problems depending on the production pattern.

We show a possibility of voluntary introduction of pollution abatement technology. A country is likely to adopt advanced pollution abatement technology to reduce pollution if it exports the polluting good. The reason is that introduction of the advanced technology improves terms of trade. This theoretical result implies that a country which produces a large amount of the polluting good to export it, which may be a developed country, tends to introduce the pollution-reducing technology voluntarily.

This paper focuses on the inter-industry and international interaction caused by pollution. We may obtain general results if we describe the cost function of technology transfer explicitly. One possible extension is to develop a new model to consider the strategic behavior of countries toward pollution abatement technology.

Appendix A

In this Appendix, we consider the relationship between $\widetilde{G}^{\alpha}(p, m^{\alpha}, v^{\alpha})$ and $\widetilde{R}^{\alpha}(q^{\alpha}, v^{\alpha})$. Since the GDP function, $\widetilde{G}^{\alpha}(\cdot)$, is linearly homogeneous in p and m^{α}, it can be rewritten as follows:

$$\begin{aligned}
\widetilde{G}^{\alpha}(p, m^{\alpha}, v^{\alpha}) &= \max_{v} m^{\alpha}(D^{\alpha}) \left\{ \frac{p}{m^{\alpha}(D^{\alpha})} F_M^{\alpha}(v_M^{\alpha}) + F_A^{\alpha}(v_A^{\alpha}) \mid v_M^{\alpha} + v_A^{\alpha} = v^{\alpha} \right\} \\
&= m^{\alpha}(D^{\alpha}) \max_{v} \{ q^{\alpha} F_M^{\alpha}(v_M^{\alpha}) + F_A^{\alpha}(v_A^{\alpha}) \mid v_M^{\alpha} + v_A^{\alpha} = v^{\alpha} \} \\
&= m^{\alpha}(D^{\alpha}) \widetilde{R}^{\alpha}(q^{\alpha}, v^{\alpha}).
\end{aligned}$$

From the properties of the GDP function, we have $\widetilde{G}_p^{\alpha} = Q_M^{\alpha}$ (e.g., Helpman, 1984). Thus, we derive $\widetilde{G}_p^{\alpha} = m^{\alpha} \widetilde{R}_q^{\alpha} \frac{\partial q^{\alpha}}{\partial p} = \widetilde{R}_q^{\alpha} = Q_M^{\alpha}$.

Appendix B

In this Appendix, we consider the sign of the Jacobian determinant of the system (4)-(8), Δ, and its implications. Totally differentiating equations (4)-(8) and choosing $E_u^j \equiv 1$, we obtain

$$\begin{aligned}
\Delta \equiv & \left[M_1(b\lambda^{\alpha} - \lambda^{\beta}) + M_2(b\lambda^{\beta} - \lambda^{\alpha}) \right] \frac{R_{qq}^{\alpha} R_{qq}^{\beta} p^2 m^{\alpha\prime} m^{\beta\prime}}{(m^{\alpha})^2 (m^{\beta})^2} \\
& - Z \left[1 + \frac{\lambda^{\alpha} R_{qq}^{\alpha} p m^{\alpha\prime}}{(m^{\alpha})^2} + \frac{\lambda^{\beta} R_{qq}^{\beta} p m^{\beta\prime}}{(m^{\beta})^2} + (1 - b^2) \frac{\lambda^{\alpha} \lambda^{\beta} R_{qq}^{\alpha} R_{qq}^{\beta} p^2 m^{\alpha\prime} m^{\beta\prime}}{(m^{\alpha})^2 (m^{\beta})^2} \right] \\
& + E_{pu}^{\alpha} r^{\alpha} \left[M_1 + (M_1 - bM_2) \frac{\lambda^{\beta} R_{qq}^{\beta} p m^{\beta\prime}}{(m^{\beta})^2} \right] + E_{pu}^{\beta} r^{\beta} \left[M_2 + (M_2 - bM_1) \frac{\lambda^{\alpha} R_{qq}^{\alpha} p m^{\alpha\prime}}{(m^{\alpha})^2} \right] \\
& - M_1 \frac{R_{qq}^{\alpha} p m^{\alpha\prime}}{(m^{\alpha})^2} - M_2 \frac{R_{qq}^{\beta} p m^{\beta\prime}}{(m^{\beta})^2},
\end{aligned}$$

where $M_1 \equiv \frac{\lambda^{\alpha} R_{qq}^{\alpha}}{m^{\alpha}} + b \frac{\lambda^{\beta} R_{qq}^{\beta}}{m^{\beta}} > 0$, $M_2 \equiv b \frac{\lambda^{\alpha} R_{qq}^{\alpha}}{m^{\alpha}} + \frac{\lambda^{\beta} R_{qq}^{\beta}}{m^{\beta}} > 0$, $Z \equiv z_{pp} - (E_p^{\beta} - R_q^{\beta})(E_{pu}^{\beta} - E_{pu}^{\alpha})$, $z_{pp} \equiv E_{pp}^{\alpha} + E_{pp}^{\beta} - \frac{R_{qq}^{\alpha}}{m^{\alpha}} - \frac{R_{qq}^{\beta}}{m^{\beta}} < 0$, $r^{\alpha} \equiv (pR_q^{\alpha} - m^{\alpha} R^{\alpha}) \frac{m^{\alpha\prime}}{m^{\alpha}}$, and $r^{\beta} \equiv (pR_q^{\beta} - m^{\beta} R^{\beta}) \frac{m^{\beta\prime}}{m^{\beta}}$.

We consider the dynamic system consisting of equations (4)-(7) and $\dot{p} = E_p^{\alpha}(p, u^{\alpha}) + E_p^{\beta}(p, u^{\beta}) - R_q^{\alpha}(q^{\alpha}) - R_q^{\beta}(q^{\beta})$. Linearizing the system at the equilibrium values of the variables, we derive $\dot{p} = (-\Delta J^{-1})dp$ where $J \equiv 1 + \frac{\lambda^\alpha R^\alpha_{qq} p m^{\alpha\prime}}{(m^\alpha)^2} + \frac{\lambda^\beta R^\beta_{qq} p m^{\beta\prime}}{(m^\beta)^2} + (1-b^2)\frac{\lambda^\alpha \lambda^\beta R^\alpha_{qq} R^\beta_{qq} p^2 m^{\alpha\prime} m^{\beta\prime}}{(m^\alpha)^2 (m^\beta)^2}$.

Let us examine the sign of J. Using equation (5), we can rewrite the second term of J as

$$\frac{\lambda^\alpha R^\alpha_{qq} p m^{\alpha\prime}}{(m^\alpha)^2} = q^\alpha \frac{R^\alpha_{qq}}{Q^\alpha_M}\left(D^\alpha \frac{m^{\alpha\prime}}{m^\alpha} - b\lambda^\beta Q^\beta_M \frac{m^{\alpha\prime}}{m^\alpha}\right) < 0.$$

We define $\epsilon^\alpha_q \equiv q^\alpha \frac{R^\alpha_{qq}}{Q^\alpha_M}$ and $\epsilon^\alpha_D \equiv D^\alpha \frac{m^{\alpha\prime}}{m^\alpha}$. ϵ^α_q and ϵ^α_D indicate the virtual price elasticity of output of M and the pollution elasticity of productivity losses in the donor country, respectively. Then, we obtain

$$\frac{\lambda^\alpha R^\alpha_{qq} p m^{\alpha\prime}}{(m^\alpha)^2} = \epsilon^\alpha_q \left(\epsilon^\alpha_D - b d^\beta \frac{m^{\alpha\prime}}{m^\alpha}\right) < 0. \tag{A.1}$$

Similarly, the third term of J can be rewritten as

$$\frac{\lambda^\beta R^\beta_{qq} p m^{\beta\prime}}{(m^\beta)^2} = \epsilon^\beta_q \left(\epsilon^\beta_D - b d^\alpha \frac{m^{\beta\prime}}{m^\beta}\right) < 0, \tag{A.2}$$

where $\epsilon^\beta_q \equiv q^\beta \frac{R^\beta_{qq}}{Q^\beta_M}$ and $\epsilon^\beta_D \equiv D^\beta \frac{m^{\beta\prime}}{m^\beta}$.

From equations (A.1) and (A.2), J can be rewritten as

$$\begin{aligned} J &= 1 + \epsilon^\alpha_q \epsilon^\alpha_D + \epsilon^\beta_q \epsilon^\beta_D - \left(b d^\beta \epsilon^\alpha_q \frac{m^{\alpha\prime}}{m^\alpha} + b d^\alpha \epsilon^\beta_q \frac{m^{\beta\prime}}{m^\beta}\right) \\ &\quad + (1-b^2)\epsilon^\alpha_q \epsilon^\beta_q \left(\epsilon^\alpha_D - b d^\beta \frac{m^{\alpha\prime}}{m^\alpha}\right)\left(\epsilon^\beta_D - b d^\alpha \frac{m^{\beta\prime}}{m^\beta}\right). \end{aligned}$$

We know that the last two terms are positive. In this paper, we assume that $1 + \epsilon^\alpha_q \epsilon^\alpha_D + \epsilon^\beta_q \epsilon^\beta_D > 0$. This assumption implies that the absolute values of the elasticities are not so large and either the absolute value of ϵ^j_q or ϵ^j_D is smaller than unity. Hence, we obtain $J > 0$. Since $\dot{p} = (-\Delta J^{-1})dp$, Δ is positive if the equilibrium is locally Walrasian stable.

Finally, we consider the implications of the positive sign of J. From equations (5) and (7), under the fixed world price, we obtain $\frac{\partial D^\alpha}{\partial \lambda^\beta} = b R^\beta_q J^{-1}$ and $\frac{\partial D^\beta}{\partial \lambda^\alpha} = b R^\alpha_q J^{-1}$. Thus, $J > 0$ under $b > 0$ denotes that an increase of the emission rate in one country, λ^j, results in an increase of pollution in the other country, D^i $(i \neq j)$. Especially, $J > 0$ under $b = 1$ also implies $\frac{\partial D^\alpha}{\partial \lambda^\alpha} = R_q^\alpha J^{-1} > 0$ and $\frac{\partial D^\beta}{\partial \lambda^\beta} = R_q^\beta J^{-1} > 0$. Moreover, $J > 0$ under $b = 0$ indicates $\frac{\partial D^\alpha}{\partial \lambda^\alpha} = R_q^\alpha \left(1 + \frac{\lambda^\alpha R_{qq}^\alpha p m^{\alpha\prime}}{(m^\alpha)^2}\right)^{-1} = R_q^\alpha (1 + \epsilon_q^\alpha \epsilon_D^\alpha)^{-1} > 0$ and $\frac{\partial D^\beta}{\partial \lambda^\beta} = R_q^\beta \left(1 + \frac{\lambda^\beta R_{qq}^\beta p m^{\beta\prime}}{(m^\beta)^2}\right)^{-1} = R_q^\beta (1 + \epsilon_q^\beta \epsilon_D^\beta)^{-1} > 0$ because $1 + \epsilon_q^\alpha \epsilon_D^\alpha + \epsilon_q^\beta \epsilon_D^\beta > 0$.

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