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ENVIRONMENTAL POLICY AND INDUCED TECHNOLOGICAL CHANGE: A TWO-REGION MODEL ANALYSIS

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ABSTRACT

This paper employs a cost-effectiveness criterion to examine the impact of policy-induced technological change on optimal abatement and emission taxes in a two-region dynamic model of transboundary pollution. We conduct theoretical and numerical simulation analysis to examine the effect of pollution abatement technology through learning by doing (LBD) and knowledge spill-over on optimal abatement and emission taxes in each region. The government in each region chooses an abatement level that minimizes costs under the presence of induced technological change (ITC) in aggregate, and for individual regions. We examine this effect on optimal abatement level and tax rate in first-best and regional optimality scenarios. Analysis reveals that ITC and LBD reduce abatement costs. Case-specific optimal abatement and costs vary with the presence of ITC and transboundary pollution. Also, spill-over effects result in different optimal tax rates in each region. We verify optimal abatement and emission tax paths for regions through numerical simulation.

Key words: *environmental policy, induced technological change, cost-effective, Transboundary pollution, spill-over, learning effect*
JEL Classification: H23, O33, Q55

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1. Introduction

In recent years, improvements in the standard of living have resulted in increased energy consumption. Along with a heavier consumption of energy is the rapid increase in related greenhouse gas (GHG) emissions, such as carbon dioxide (CO_2), into the atmosphere. Such environmental damage not only happens within a region but also extends to other regions. An example of the transboundary nature of environmental pollution (i.e. emission) is carbon leakage. Reduced emissions in an abating region may increase emissions in a non-abating region. Emission reducing behaviour in a certain region can increase emissions in the non-abating region. This occurs when carbon intensive industry from a pollutant-abating region transfers to a non-abating region. This has a positive influence on economic activity but a negative effect on the environment. Providing solutions to this transboundary environmental problem might be difficult, but is possible. Regions can re-evaluate domestic environmental polices and consider how these policies can affect other regions. Among solutions that are currently explored in the literature are technology and knowledge spill-over. Diffusion of technology and abatement know-how is essential for achieving large-scale emission reduction and eventual offsetting of transboundary pollution.

Several studies since the 1990s analyse transboundary pollution problems between two regions. Xepapadeas (1995) examines this issue in a global optimum and individual country optimum under dynamic setting. The study considers knowledge as a common pool in first-best and R&D-based knowledge accumulation cases. Golombek and Hoel (2004) analyse carbon leakage with endogenous technological change and technology spill over. On the other hand, previous studies of Goulder and Schneider (1999), Goulder and Mathai (2000), Buonanno et al. (2003), Rosendahl(2004) also explore policy-induced technological change in promoting emission reduction. Goulder and Mathai (2000) investigate how induced technological change (ITC) influences optimal abatement and carbon-emissions tax paths using cost-effectiveness and cost-benefit policy criteria. They analyse knowledge accumulation by assuming different effects of research and development (R&D) and learning by doing (LBD). These literatures on endogenous technological change and environmental policy are discussed in Loschel (2002). Rosendahl (2004) extended Goulder and Mathai's (2000) model by examining how ITC influences cost-effectiveness of LBD and knowledge spill-over. However, these studies did not consider transboundary pollution.

This paper extends the Rosendahl (2004) model by positing a policymaker imposing a cost-effectiveness standard. We analyse transboundary pollution in an asymmetric two-region model. Although each region discharges pollutants (CO_2), the extension assumes unilateral spill-over. Pollutants flow only from the developed region to developing regions. This one-way spill-over phenomenon reduces pollutant levels from the source. However, pollution levels rise in recipient regions. A possible solution to such transboundary pollution problems is another type of spill-over. This paper proposes a spill-over effect of knowledge through pollution reduction technologies that are usually transferred and diffused from advanced and developing regions. One such example is the Clean Development Mechanism (CDM). Assuming a spill-over effect of knowledge and pollution, we explore how ITC influences the cost-effectiveness optimal tax policy and emission reduction decisions.

The structure of this paper is as follows. Section 2 presents the model and derives optimality for global regions and for individual cases respectively. Section 3 introduces and examines optimal tax policies in each case. Section 4 presents numerical simulations. Section 5 concludes and identifies future areas of research.

2. The model

In this section, we present a two-region ($j = F, G$) asymmetric model of transboundary pollution. The model assumes that optimal abatement decision includes a one-way spill-over effect. In addition, the model examines ITC using the cost-effectiveness criterion. Analysis reveals that ITC reduces abatement costs. However, case-specific optimal abatement and costs vary in each region and across regions with ITC and transboundary pollution.

2.1. Model Setting

One-way spill-over pollution flows from the developed region F to the developing region G. The source region F, experiences a reduction in pollutant levels, whereas G, the region catching the spill-over, suffers from increased emissions. To resolve this transboundary problem, region F responds by leaking its own pollution-reduction knowledge to region G.

We assume that producers are competitive and minimize total costs. Let $C^j(A_t^j, H_t^j)$ be the aggregate abatement cost function at time t in region j, where A_t^j denotes abatement levels, and H_t^j denotes the stock of knowledge or the level of technology. The function is assumed to have the following properties: $C_A^j(\cdot) > 0, C_{AA}^j(\cdot) > 0, C_H^j(\cdot) < 0$ and $C_{AH}^j(\cdot) < 0$. That is, the first two properties imply that costs are an increasing and convex function of abatement. In addition, knowledge reduces costs and decreases both total and marginal abatement costs. Abatement is an emission reduction compared to a fixed business-as-usual emission path $E_t^{0,j}$. We assume that $\lim_{A^j \to E^{0,j}} C_A^j = \infty$ to avoid negative emission levels.

Pollution accumulation is expressed as

$$\dot{S}_t^F = -\delta^F S_t^F + (1-\varepsilon)(E_t^{0,F} - A_t^F),$$
$$\dot{S}_t^G = -\delta^G S_t^G + (E_t^{0,G} - A_t^G) + \varepsilon(E_t^{0,F} - A_t^F),$$

where δ^j is the natural rate of pollution removal in each region, S_t^j is the pollutant concentration, $E_t^{0,j}$ is baseline emissions, and the pollutant that flows from region F to region G is $0 \le \varepsilon \le 1$. The first term of pollution accumulation in each region represents the net of natural removal $\delta^j S_t^j$. Furthermore, $(E_t^{0,F} - A_t^F)$ represents the emission at time t in region F , and $\varepsilon(E_t^{0,F} - A_t^F)$ shows emissions from region F according to transboundary pollution.[1] We calculated the expressions for regions F and G by deducting the net of natural removal $(\delta^j S_t^j)$ from those emissions. With transboundary pollution, the pollution level falls in region F , whereas it rises in region G.

We write knowledge accumulation as

$$\dot{H}_t^j = \alpha^j H_t^j + k^j \psi^j (A_t^j, H_t^j) + l^j \theta^j (H_t^i, H_t^j),\ j = F, G, \quad i \ne j,$$

where α^j is the rate of autonomous technological change in region j or the exogenous technological change rate. The first term expresses the autonomous technological change at the rate α^j. In addition, k^j is the parameter that shows the degree to which the ITC in region j exists when $0 \le k^j \le 1$. The second term indicates LBD effect when $k^j > 0$ and an ITC is introduced through LBD effect. Also, $\psi^j(A_t^j, H_t^j)$ is knowledge accumulation function in region j such that $\psi^j(\cdot) > 0, \psi_A^j(\cdot) > 0$ and $\psi_{AA}^j(\cdot) < 0$. Technological diffusion from region i to region j is l^j. Technological diffusion function is $\theta^j(H_t^i, H_t^j)$, and is a non-decreasing function in H_t^i, but a non-increasing function in H_t^j. Thereby, technological diffusion is slower when the technological gap between the two regions is smaller. The third term shows diffusion effect of the technology when $l^j > 0$.

2.2. The first-best solution

We initially derive the first-best solution: optimal abatement in global emissions. A social planner chooses abatement levels that minimize abatement costs. The optimal time path in the infinite future is chosen.

The optimisation problem is as follows:

$$\min_{A_t^F, A_t^G} \int_0^\infty e^{-rt} (C^F (A_t^F, H_t^F) + C^G (A_t^G, H_t^G)) dt$$

[1] At time t, total emission E_t is shown as $E_t = (E_t^{0,F} - A_t^F) + (E_t^{0,G} - A_t^G) = E_t^F + E_t^G$. Individual emission is denoted by $E_t^j = E_t^{0,j} - A_t^j$.

$$
\begin{aligned}
s.t.\quad & \dot{S}_t^F = -\delta^F S_t^F + (1-\varepsilon)(E_t^{0,F} - A_t^F), \\
& \dot{S}_t^G = -\delta^G S_t^G + (E_t^{0,G} - A_t^G) + \varepsilon(E_t^{0,F} - A_t^F), \\
& \dot{H}_t^F = \alpha^F H_t^F + k^F \psi^F (A_t^F, H_t^F) + l^F \theta^F (H_t^F, H_t^G), \\
& \dot{H}_t^G = \alpha^G H_t^G + k^G \psi^G (A_t^G, H_t^G) + l^G \theta^G (H_t^F, H_t^G), \\
& S_t^j \le \bar{S}^j, \forall t, \\
& H^j(0) = H_0^j, \quad S^j(0) = S_0^j, \quad j = F, G,
\end{aligned}
$$

where r is the interest rate, S_t^j is the current stock level, and $\bar{S}^j$ is the given target environmental constraint. $S_t^j \le \bar{S}^j$ implies that the environmental constraint should not exceed the given target $\bar{S}^j$ in any period.

The current value Hamiltonian to solve this problem is the following:

$$
\begin{aligned}
H(A^F, A^G, H^F, H^G, S^F, S^G, \tau^F, \tau^G, \mu^F, \mu^G, t) \\
= -[C^F(A_t^F, H_t^F) + C^G(A_t^G, H_t^G)] \\
- \tau_t^F[-\delta^F S_t^F + (1-\varepsilon)(E_t^{0,F} - A_t^F)] \\
- \tau_t^G[-\delta^G S_t^G + (E_t^{0,G} - A_t^G) + \varepsilon(E_t^{0,F} - A_t^F)] \\
+ \mu_t^F[\alpha^F H_t^F + k^F \psi^F (A_t^F, H_t^F) + l^F \theta^F (H_t^F, H_t^G)] \\
+ \mu_t^G[\alpha^G H_t^G + k^G \psi^G (A_t^G, H_t^G) + l^G \theta^G (H_t^F, H_t^G)]
\end{aligned}
$$

where τ_t^F, τ_t^G is the shadow cost of the pollution stock for each region and μ_t^F, μ_t^G is the shadow prices of the knowledge stock. Moreover, given the environmental constraint of $S_t^j \le \bar{S}^j$, we form the following Lagrangian:

$$L_t = H_t + \eta_t^F(\bar{S}^F - S_t^F) + \eta_t^G(\bar{S}^G - S_t^G).$$

Assuming an interior solution, the following necessary conditions for a maximum principle are obtained.

$$\frac{\partial L}{\partial A^F} = 0 \Rightarrow \quad C_A^F(A_t^F, H_t^F) = (1-\varepsilon)\tau_t^F + \varepsilon\tau_t^G + \mu_t^F k^F \psi_A^F(A_t^F, H_t^F) \tag{1}$$

$$\frac{\partial L}{\partial A^G} = 0 \Rightarrow \quad C_A^G(A_t^G, H_t^G) = \tau_t^G + \mu_t^G k^G \psi_A^G(A_t^G, H_t^G) \tag{2}$$

$$-\dot{\tau}^j = r^j(-\tau^j) - \frac{\partial L}{\partial S^j} \Rightarrow \quad \dot{\tau}_t^j = (r^j + \delta^j)\tau_t^j - \eta_t^j \tag{3}$$

$$\dot{\mu}^F = r^F \mu^F - \frac{\partial L}{\partial H^F} \Rightarrow \dot{\mu}_t^F = \mu_t^F(r^F - \alpha^F - k^F \psi_{H^F}^F(\cdot) - l^F \theta_{H^F}^F(\cdot)) + C_{H^F}^F(\cdot) - \mu_t^G l^G \theta_{H^F}^G(\cdot) \tag{4}$$

$$\dot{\mu}^G = r^G \mu^G - \frac{\partial L}{\partial H^G} \Rightarrow \dot{\mu}_t^G = \mu_t^G (r^G - \alpha^G - k^G \psi_{H^G}^G(\cdot) - l^G \theta_{H^G}^G(\cdot)) + C_{H^G}^G(\cdot) - \mu_t^F l^F \theta_{H^G}^F(\cdot) \quad (5)$$

The transversality condition is as follows:

$$\lim_{t\to\infty} e^{-rt} \tau_t^j S_t^j = 0, \quad (6)$$

$$\lim_{t\to\infty} e^{-rt} \mu_t^j H_t^j = 0. \quad (7)$$

Integrating Eq.(3), using the transversality condition as the boundary condition yields

$$\tau_t^j = \int_t^\infty \eta_s^j e^{-(r^j+\delta^j)(s-t)} ds. \quad (8)$$

Optimal abatement in the two regions is

$$C_A^F(A_t^F, H_t^F) - \mu_t^F k^F \psi_A^F(A_t^F, H_t^F) = (1-\varepsilon)\tau_t^F + \varepsilon \tau_t^G, \quad (9)$$

$$C_A^G(A_t^G, H_t^G) - \mu_t^G k^G \psi_A^G(A_t^G, H_t^G) = \tau_t^G. \quad (10)$$

The first terms of the left side of Eqs. (9) and (10) refer to marginal abatement costs in each region; the second terms show the marginal value of the future technical progress for the current abatement. The shadow cost of the pollution in the right-hand side changes with each region. It is equal to one's own shadow cost of pollution in region G. Environmental costs must be paid when region F exudes the shadow cost of the pollutant until region G. Region F must consider not only its own region's shadow cost, but also shadow cost from region G. Let us consider the following ε cases in region F. If $\varepsilon = 0$, the present value of the marginal abatement costs and LBD effect is equal to τ_t^F, as in region G. If $\varepsilon > 0$, region F must consider not only its own, but also the environmental damage imparted to region G.

Next, we consider the ITC's impact on the abatement by increasing parameter k^j from 0 to 1. We differentiate Eq. (9) with respect to k^F. Evaluating it at $k^F = 0$, we obtain,

$$\frac{\partial A^F(t,k^F)}{\partial k^F} = \frac{(1-\varepsilon)\frac{\partial \tau^F(t,k^F)}{\partial k^F} + \varepsilon \frac{\partial \tau^G(t,k^F)}{\partial k^F} + \mu^F(t,k^F)\psi_A^F - C_{AH}^F \frac{\partial H^F(t,k^F)}{\partial k^F}}{C_{AA}^F}. \quad (11)$$

In Eq. (11), we find that the presence of ITC has three effects: 1) a shadow cost effect, which is the first term in the numerator, $(\partial \tau^j(t,k^F)/\partial k^F \le 0)$; 2) an LBD effect given by the second term is the $(\mu^F(t,k^F)\psi_A^F > 0)$; and 3) knowledge-growth effect, $(-C_{AH}^F(\partial H^F(t,k^F)/\partial k^F) > 0)$. [2] The LBD effect refers to the additional marginal benefit from emission reduction. The abatement level increases with increasing knowledge because of ITC, but decreases otherwise. Moreover, ITC lowers

[2] Refer to Appendix for Goulder and Mathai (2000)'s proof for this inequality.

costs and shadow cost of pollution. The influence of k^F in A_t^F and the net effect of the abatement at arbitrary time t including $t=0$ are indeterminate.

Holding knowledge H^F constant at $t=0$, the effect of k^F to abatement A_0^F in the early stages is,

$$\frac{\partial A^F(0,k^F)}{\partial k^F}=\frac{(1-\varepsilon)\frac{\partial \tau^F(t,k^F)}{\partial k^F}+\varepsilon\frac{\partial \tau^G(t,k^F)}{\partial k^F}+\mu^F(0,k^F)\psi_A^F}{C_{AA}^F}. \tag{12}$$

The expression does not show lower initial abatement. The sign is indeterminate unless it is shown clearly how many additional pollutants cause damage in each region under transboundary pollution. However, if the LBD effect is greater than shadow cost effect, early abatement increases.

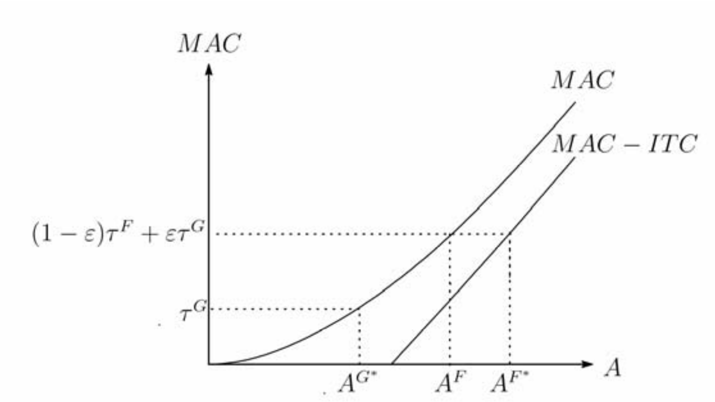

Figure 1: The marginal abatement cost curve under optimality in first-best case

Differentiating Eq.(10) with respect to k^F and then assuming $k^G=0$, yields:

$$\frac{\partial A^G(t,k^F)}{\partial k^F}=\frac{\frac{\partial \tau^G(t,k^F)}{\partial k^F}-C_{AH}^G\frac{\partial H^G(t,k^F)}{\partial k^F}}{C_{AA}^G}. \tag{13}$$

The second term in the numerator shows that when ITC in region F increases, diffusion of knowledge to region G also increases. However, while the second term is positive, the whole term is indeterminate. With the relation between a shadow cost effect and knowledge growth effect, ITC effect on the abatement are also indeterminate. However, because knowledge stock is fixed in the early stages, early abatement A_0^G is as follows:

$$\frac{\partial A^G(0,k^F)}{\partial k^F} = \frac{\frac{\partial \tau^G(0,k^F)}{\partial k^F}}{C_{AA}^G} \leq 0. \qquad (14)$$

Given a fixed knowledge stock, initial abatement declines. Fig. 2 sets up the marginal abatement cost curve in the first-best case. The two regions have identical marginal abatement cost curves (MACs); the MAC-ITC curve is drawn on Fig. 2. The marginal abatement cost function and knowledge stock in the early stage are the same in two regions. (From the assumption of $C_A^j(0, H^j) = 0$ that the assumption of abatement cost function and the marginal abatement costs that were assumed increasing from zero and the assumption of the knowledge accumulation function.) When $k^G = 0$, ITC does not exist in region G. In region F, abatement increases when ITC exists ($k^F = 1$). Abatement in region F is greater than in region G.

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2. 3. Regional optimality

This section presents examinations of each region when only its own welfare is considered. We consider only the problem faced by one region, and we take as given the other region's behaviour. Abatement costs are minimized. Region F chooses optimal time path A_t^F in the future. The optimization problem is as follows:

$$\min_{A_t^F} \int_0^\infty e^{-rt}(C^F(A_t^F, H_t^F))dt$$

$$\begin{aligned}
s.t. \quad & \dot{S}_t^F = -\delta^F S_t^F + (1-\varepsilon)(E_t^{0,F} - A_t^F), \\
& \dot{H}_t^F = \alpha^F H_t^F + k^F \psi^F(A_t^F, H_t^F) + l^F \theta^F(H_t^F, H_t^G), \\
& \dot{H}_t^G = \alpha^G H_t^G + k^G \psi^G(A_t^G, H_t^G) + l^G \theta^G(H_t^F, H_t^G), \\
& S_t^F \leq \bar{S}^F, \quad \forall t, \\
& H^j(0) = H_0^j, \quad S^F(0) = S_0^F.
\end{aligned}$$

Moreover, given the environmental constraint of $S_t^F \leq \bar{S}^F$, we form the following Lagrangian:

$$L_t = H_t + \eta_t^F(\bar{S}^F - S_t^F).$$

Assuming an interior solution, we have the following necessary condition:

$$C_A^F(A_t^F, H_t^F) - \mu_t^F k^F \psi_A^F(A_t^F, H_t^F) = (1-\varepsilon)\tau_t^F, \qquad (15)$$

$$\dot{\tau}_t^F = (r^F + \delta^F)\tau_t^F - \eta_t^F. \qquad (16)$$

The succeeding expressions minimize costs only in region G, choosing an optimal time path A_t^G in the future. This optimization problem is as follows:

$$\min_{A_t^G} \int_0^\infty e^{-rt} (C^G(A_t^G, H_t^G))dt$$

$$\begin{aligned} s.t. \quad & \dot{S}_t^G = -\delta^G S_t^G + (E_t^{0,G} - A_t^G) + \varepsilon(E_t^{0,F} - A_t^F), \\ & \dot{H}_t^F = \alpha^F H_t^F + k^F \psi^F (A_t^F, H_t^F) + l^F \theta^F (H_t^F, H_t^G), \\ & \dot{H}_t^G = \alpha^G H_t^G + k^G \psi^G (A_t^G, H_t^G) + l^G \theta^G (H_t^F, H_t^G), \\ & S_t^G \le \bar{S}^G, \quad \forall t, \\ & H^j(0) = H_0^j, \quad S^G(0) = S_0^G. \end{aligned}$$

Moreover, given the environmental constraint $S_t^G \le \bar{S}^G$, we form the following Lagrangian:

$$L_t = H_t + \eta_t^G (\bar{S}^G - S_t^G).$$

Again, the necessary condition for an interior solution is

$$C_A^G (A_t^G, H_t^G) - \mu_t^G k^G \psi_A^G (A_t^G, H_t^G) = \tau_t^G, \qquad (17)$$

$$\dot{\tau}_t^G = (r^G + \delta^G)\tau_t^G - \eta_t^G. \qquad (18)$$

When the LBD effect is taken into account, the marginal abatement cost in region G is equal to τ_t^G, which is the same as the case of the first-best solution. However, because pollutant level rises as a result of transboundary pollution, marginal damage must be contained. Unlike the first-best solution, only the region itself is considered in region F. The transboundary pollution costs to region ($\varepsilon \cdot \tau_t^G$) are not considered in Eq. (15).

Next, we analyse the influence of ITC in region F because it is the same as the first-best case in region G. Differentiating Eq.(15) with respect to k^F and evaluating it at $k^F = 0$, we obtain,

$$\frac{\partial A^F(t, k^F)}{\partial k^F} = \frac{(1-\varepsilon)\frac{\partial \tau^F(t,k^F)}{\partial k^F} - C_{AH}^F \frac{\partial H^F(t,k^F)}{\partial k^F}}{C_{AA}^F}. \qquad (19)$$

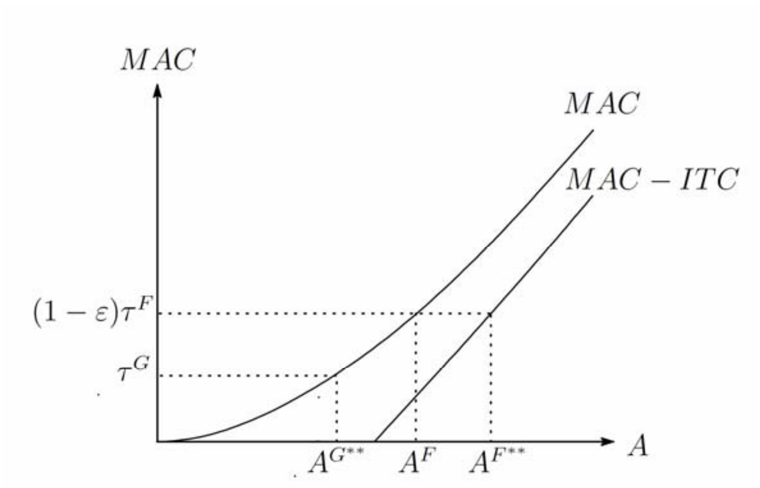

Figure 2: The marginal abatement cost curve under optimality in each region

Although transboundary pollution is considered, the influence of ITC is indeterminate when we have a negative shadow cost effect and a positive knowledge growth effect. At $t=0$, because the knowledge stock is being fixed, the early abatement A_0^F is

$$\frac{\partial A^F(0,k^F)}{\partial k^F} = \frac{(1-\varepsilon)\frac{\partial \tau^F(0,k^F)}{\partial k^F}}{C_{AA}^F} \le 0. \qquad (20)$$

In Eq. (20), we have shadow cost effect and observe a decline in early emission reduction only in region F. Fig. 3 shows a scenario that resembles the first-best case in region G. Abatement increases in aggregate when ITC exists. In regional optimality case, marginal abatement cost and abatement decrease in region F because transboundary pollution occurs. Since region F is acting only in consideration of its own region, abatement is decreasing.

3. Firm activity and optimal tax policy

In the preceding section, government determines abatement. This section examines application of an optimal emission tax in each region when a firm initiates abatement policy. The individual firm responds to the social optimum to achieve optimal abatement. We consider N identical firms exist in each region and there is an optimal tax policy. The representative firm (denoted by a lower-case letter) considers the following cost minimization problem:

$$\min_{a_t^s} \int_0^\infty e^{-rt}(c^j(a_t^s, h_t^s) + t_t^j(e_t^{0,s} - a_t^s))dt$$
$$= \int_0^\infty e^{-rt}\left(\frac{1}{N}C^j(Na_t^s, h_t^s) + t_t^j(e_t^{0,s} - a_t^s)\right)dt$$

$$s.t. \quad \dot{h}_t^s = \alpha^j h_t^s + k^j \psi^j (\varphi N a_t^s + (1-\varphi^j) A_t^j, h_t^s),$$
$$h^s(0) = h_0^s, s, j \in \{F, G\}.$$

An individual firm level is denoted in lower case letters. We denote t^j as emission tax in region j and $e_t^{0,s}$ as emission level. Equilibrium is $a_t^s = A_t^j/N$, $h_t^s = H_t^j$. Learning effect in each firm depends on a weighted sum of abatement within the firm and total abatement in the region. The firm's LBD function is $\psi^j(\varphi^j N a_t^s + (1-\varphi^j) A_t^j, h_t^s)$, where φ^j is a parameter ($0 \le \varphi^j \le 1$). The LBD effect can have entirely internal or external effects on individual firms. By an internal learning effect, the firm's activity influences knowledge accumulation. An external effect is obtained independently of the firm's activity. Here, $\varphi^j = 1(0)$ means that ITC is entirely an internal (external) learning effect. The ITC is a totally internal effect with LBD. The spill-over effect $\varphi^j = 0$ suggests that ITC only occurs in a region because of spill-over.

To solve the optimization problem, we set up a current value Hamiltonian and assume an interior solution. The necessary condition is:

$$C_A^j(A_t^j, H_t^j) = \varphi^j \mu_t^j k^j \psi_A^j(A_t^j, H_t^j) + t_t^j, \quad j = F, G, \quad (21)$$

where μ_t^s is a shadow price of knowledge. It is $\mu_t^s = \mu_t^j/N$. We then substitute Eq. (21) into Eqs. (1) and (2), thereby obtaining:

$$t_t^F - (1-\varphi^F)\mu_t^F k^F \psi_A^F(A_t^F, H_t^F) = (1-\varepsilon)\tau_t^F + \varepsilon \cdot \tau_t^G, \quad (22)$$

$$t_t^G - (1-\varphi^G)\mu_t^G k^G \psi_A^G(A_t^G, H_t^G) = \tau_t^G. \quad (23)$$

Substituting Eq. (21) into Eqs. (15) and (17), we obtain

$$t_t^F - (1-\varphi^F)\mu_t^F k^F \psi_A^F(A_t^F, H_t^F) = (1-\varepsilon)\tau_t^F, \quad (24)$$

$$t_t^G - (1-\varphi^G)\mu_t^G k^G \psi_A^G(A_t^G, H_t^G) = \tau_t^G. \quad (25)$$

These results suggest that when an external learning effect occurs, emission taxes differ between the regions. Results depend on whether the LBD effect is greater than the shadow cost. According to the internal learning effect, although emission taxes differ between regions, if the shadow cost of the pollution is equal in region F and region G and without transboundary pollution, the emission tax is equal to the shadow cost of the pollution ($t_t^j = \tau_t^j$). When $k^F = 1, k^G = 0$ and there is a spill-over effect $(\varphi^F = 0)$, whether emission tax of region F decreases or increases depends on the marginal benefit of the LBD effect and shadow costs of pollution. Emission tax will increase if the LBD effect is greater than the shadow cost of pollution. Consideration of spill-over to region G under the first-best case in region F reveals that because of shadow cost of the pollution in region F and region G , the influence of ITC is indeterminate. Moreover, emission taxes in region F will decline with reduction of the shadow cost of pollution with ITC.

4. Numerical simulation

We perform numerical simulation to evaluate the significance of our own theoretical analysis. The functional forms, parameter values and initial conditions are assumed to derive the optimal abatement path. We conduct simulation using CO_2 data. The model analyses optimal abatement and emission tax in Annex I and Non-Annex I which are defined by the Kyoto Protocol. Also, we examine the occurrence of carbon leakage between these representative regions. We assume steady state conditions that require abatement and CO_2 concentrations to remain constant in the last period. And although knowledge spill-over effects are obtained theoretically, the influence is actually investigated using numerical simulations. The LBD effect exists only in Annex I while technological change in Non-Annex I is exogenous, or caused by technological diffusion from Annex I.

4.1. Functional specification and parameter values

The functional forms and parameter values for simulation follow specifications in Rosendahl (2004) and Goulder and Mathai (2000). We assume new functional forms for CO_2 concentration in the atmosphere to simulate regional CO_2 emissions. The following functional form for the CO_2 concentration in the atmosphere for each region is used:

$$\dot{S}_t^F = \beta[(1-\varepsilon)(E_t^{0,F} - A_t^F)] - \delta(S_t^F - PIL), \quad F = AnnexI, \tag{26}$$

$$\dot{S}_t^G = \beta[(E_t^{0,G} - A_t^G) + \varepsilon(E_t^{0,F} - A_t^F)] - \delta(S_t^G - PIL), \quad G = Non-AnnexI, \tag{27}$$

where $\beta = 0.30$, $\delta = 0.008$, $S_0 = 360\,ppmv$ and $PIL = 278\,ppmv$. Following the projections of the Intergovernmental Panel on Climate Change (IPCC), the CO_2 concentration level in 2000 is taken as the initial point: 360 parts per million by volume (ppmv). Baseline emissions follow the A1 marker scenario from the IPCC's Special Report on Emission Scenarios until 2100. Here, only 30 % of current emissions contribute to the augmentation of atmospheric CO_2 . The portion of CO_2 concentration more than the preindustrial level (PIL) is removed naturally at a rate of 0.8 % per annum.

We use the following abatement cost functions from Rosendahl (2004):

$$C(A_t^F, H_t^F) = M_C^F \frac{(A_t^F)^{\alpha_{C1}^F}}{(E_t^{0,F} - A_t^F)^{\alpha_{C2}^F}} \cdot \frac{1}{H_t^F}, \quad F = AnnexI, \tag{28}$$

$$C(A_t^G, H_t^G) = M_C^G \frac{(A_t^G)^{\alpha_{C1}^G}}{(E_t^{0,G} - A_t^G)^{\alpha_{C2}^G}} \cdot \frac{1}{H_t^G}, \quad G = Non - AnnexI. \ (29)$$

We set the parameters $M_C^F = 220, \alpha_{C1}^F = 2$ and $\alpha_{C2}^F = 1$ for region F , and $M_C^G = 180, \alpha_{C1}^G = 2$ and $\alpha_{C2}^G = 1$ for region G. Abatement in region G is less costly than in region F.

For equations defining knowledge accumulation, we assume autonomous technological change at a rate of $\alpha^j = 0.0025$ in region F. The LBD effect in region F is

$$\psi^F(A_t^F, H_t^F) = M_\psi^F (A_t^F)^\gamma (H_t^F)^\phi, \quad F = AnnexI. \ (30)$$

with $M_\psi^F = 0.011, \gamma = 0.5$ and $\phi = 0.5$.

Technological diffusion from region F to region G is assumed as follows.

$$\theta^G(H_t^F, H_t^G) = \sigma^G (H_t^F - H_t^G), \quad G = Non - AnnexI. \ (31)$$

Despite an uncertain value for the diffusion parameter, Rosendahl, set $\sigma_j = 0.01$. The technical diffusion from region F causes a 1% reduction. Moreover, the initial ratio H_t^G / H_t^F is taken as H_t^G / H_t^F. We denote the existence of ITC as $k^G = 0$, ITC non-existence, while $k^F = 1$, otherwise. Parameter ε, indicates the fraction of transboundary pollution. The value of ε (carbon leakage rate) is taken as follows. With $\varepsilon = 0$, there is no transboundary pollution, whereas with $\varepsilon = 0.2$, transboundary pollution occurs. [3] When $\varepsilon = 1$, complete transboundary pollution occurs and all pollution flows from Annex I to Non-Annex I.

4.2. Simulation result

To investigate the effect of ITC, we set $k^F = 1$ as the case with ITC, and $k^G = 0$ without ITC. We assume that the CO_2 target is 555 ppmv by the year 2200, and 20% transmission through air transportation. Furthermore, we assume that carbon leakage occurs from Annex I to carbon-intensive Non-Annex I. Non-Annex I denotes region G in the model. Annex I as region F implements carbon dioxide reduction technologies. We compare first-best and regional scenarios using transboundary pollution problems.

[3] According to IPCC , the rate of carbon leakage is from 5% to 20%. We assume that there is 20% leakage in this analysis.

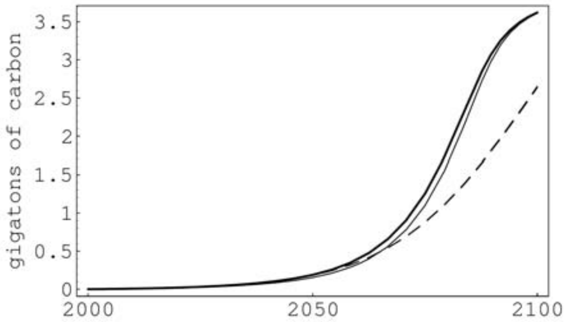

Figure 1: Optimal abatement in regional case($\varepsilon = 0.2$)

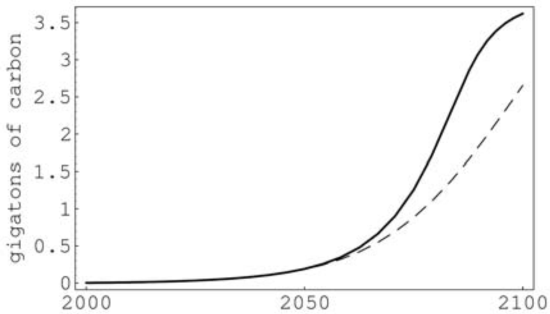

Figure 2: Optimal abatement in regional case ($\varepsilon = 0$)

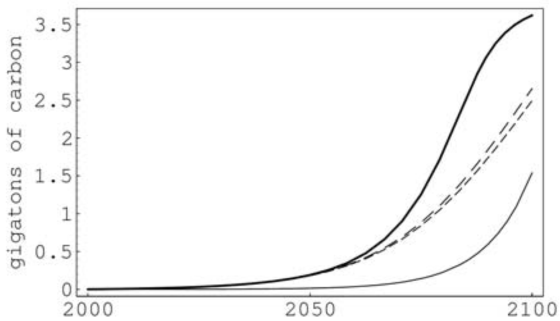

Figure 3: Optimal abatement in regional case ($\varepsilon = 1$)

Figs. 3-8 show results from simulations. In the two scenarios, a solid line expresses the optimal path of Annex I and a dotted line expresses the optimal path of Non-Annex I. The case of $\varepsilon = 0.2$ is considered in Fig. 3. According to Fig. 3, the optimal abatement path slopes upward to the concentration target. The curves slightly change when Annex I adopts first-best and regional optimality. By comparing the case where social-optimality and only own region are considered, abatement path is higher in first-best case. Also, Annex I has an abatement profile more drastic than that of Non-Annex I. Abatement falls slightly if Annex I only considers its own welfare. About the path of Non-Annex I, the change has not appeared in the first-best and individual region case. Moreover, ITC increases abatement and the abatement path suddenly changes in 2100. With ITC's existence, the abatement path slightly is steeper. Furthermore, in Figs. 4 and 5, we consider the extreme case of carbon leakage and changes in ε. When $\varepsilon = 0.2$, abatement paths of Annex I in regional case shift downward. However, when $\varepsilon = 0$, each abatement path of Annex I is similar to first-best and regional scenarios. In Figs. 3 and 4, the change in both figures does not appear about Non-Annex I. However, at $\varepsilon = 1$ which is an extreme case of transboundary pollution in Fig. 5, the change has appeared in all the cases. In Annex I's path, difference is shown and the abatement path has fallen. Although it is small, the difference is seen in Non-Annex I. Annex I's path in regional scenarios also shows a lower abatement path than Non-Annex I in both scenarios.

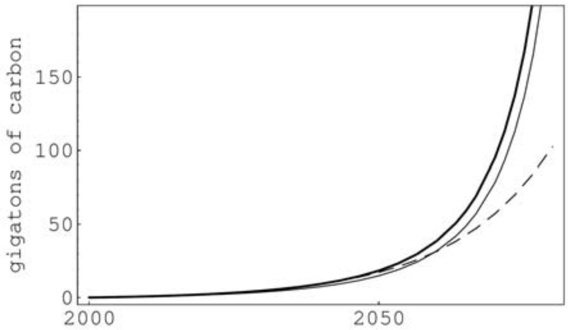

Figure 4. Optimal tax in regional case ($\varepsilon = 0.2$)

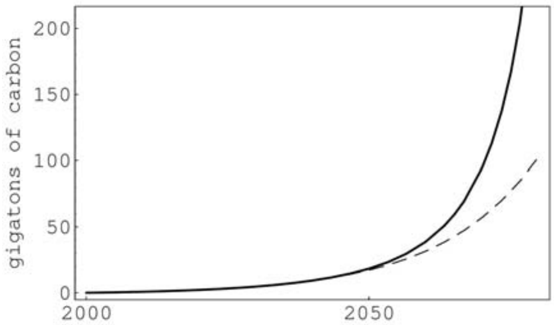

Figure 5. Optimal tax in regional case ($\varepsilon = 0$)

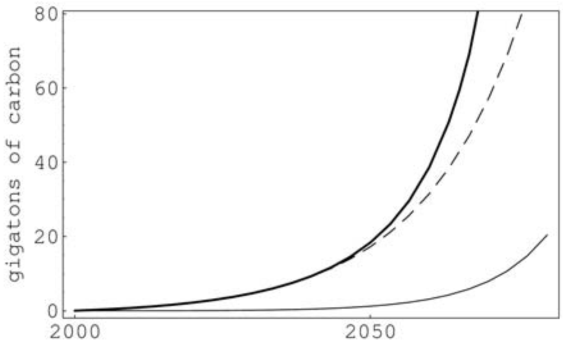

Figure 6. Optimal tax in regional case ($\varepsilon = 1$)

Next, emission tax is considered. Emission tax is influenced by carbon leakage. Figs. 6-8 analyse the effect of this carbon leakage. In Appendix (A.3) we show that optimal emission tax, in dollars per ton, takes off and grows at a rate of ($r+\delta$) for $S < \bar{S}$. A different tax rate is shown in each case. We analyze carbon leakage with ITC when the LBD effect is external in Annex I $(\varphi^F = 0)$. In Figs. 6, 7, and 8, optimal tax path for Annex I is higher than Non-Annex I in first-best and regional scenarios. Slight differences in the two scenarios of emission tax path are shown in Fig.6 while Fig.7 reports the same paths in the two scenarios, although emission tax is higher in Annex I than in Non-Annex I. However in Fig. 8, the path of Non-Annex I comes close to Annex I's. Moreover, Annex I's path in regional optimality case falls compared with Non-Annex I's. Optimal tax rate is higher in Annex I than in Non-Annex I in both cases. The result indicates that optimal tax path is different with spill-over effects.

5. Conclusion

This paper analyzes the dynamics of transboundary pollution in an asymmetric two-region model using cost effectiveness policy criterion. We used a theoretical framework and simulation in order to obtain an optimal abatement and emission tax. Our analysis shows that optimal abatement and emission taxes differ in each region. Abatement level and emission taxes differ in the first-best case and the optimality case of each government. If an external learning effect exists, optimal emission taxes differ. However, we observe no difference in absence of transboundary pollution in the case of internal learning effects. Since the costs of the developing regions that include environmental damage in the first-best case must be considered, the marginal abatement cost of the developed region increases when transboundary pollution occurs. If each government considers only its own region, then marginal abatement costs fall in the developed region. Although the manner in which the optimal abatement is influenced by ITC is indeterminate, initial abatement will increase if the LBD effect is greater than the shadow cost effect in the developed region. Moreover, initial abatement decreases in the developing region. Existence of ITC does not show that emission reduction of pollution rises throughout the entire period. However, overall abatement increases. Policy options for the regions can include emission taxes and policy-induced technological change in controlling environmental damage.

Numerical simulations indicate optimal paths from the model. When ITC exists in developed regions, abatement rises relative to developing regions. Because of the difference in LBD and spill-over effects, optimal tax rates differ in each region. Optimal taxes are higher in developed regions than in developing regions, and change with the influences of transboundary pollution. Technological growth in developing regions is mainly due to diffusion. The presence of knowledge spill-over and transboundary pollution can have significant impact on optimal abatement and emission tax. The model suggests that there is a strategic relation between regions if spill-over of transboundary pollution and knowledge exist. Although this analysis considered only tax policy with emission trading in developed countries, it is necessary to analyze its outcomes. Further detailed analysis of this phenomenon is still necessary.

APPENDIX

We analyse the slope of the optimal abatement path by examining the profile of the shadow cost of the pollution stock, τ_t^j and the shadow prices of the knowledge stock, μ_t^j. First, let us examine the slope of the emission tax path. Using Eq. (3) and when $S_t^j < \bar{S}^j$:

$$\tau_t^j = \int_t^\infty \eta_s^j e^{(r^j+\delta^j)(s-t)} ds \qquad \text{(A.1)}$$

When $t = 0$,

$$\tau_0^j = \int_0^\infty \eta_s^j e^{(r^j+\delta^j)s} ds \qquad \text{(A.2)}$$

Therefore,

$$\tau_t^j = \tau_0^j e^{(r^j+\delta^j)t} \qquad \text{(A.3)}$$

Next, we show the profile of the shadow prices of knowledge using Eqs. (4) and (5).

$$\dot{\mu}_t^j = (r^j - \alpha^j - k^j\psi_{H^j}^j(\cdot) - l^j\theta_{H^j}^j(\cdot))\mu_t^j + C_{H^j}^j(\cdot) - \mu_t^i l^i \theta_{H^j}^i(\cdot), \quad i, j \in \{F, G\}, i \neq j \quad \text{(A.4)}$$

Taking the transversality conditions in Eq. (7) and integrating Eqs. (4) and (5), we obtain the following.

$$\mu_t^j = -\int_t^\infty (C_{H^j}^j(\cdot) - \mu_t^i l^i \theta_{H^j}^i(\cdot)) e^{-(r^j-\alpha^j-k^j\psi_{H^j}^j(\cdot)-l^j\theta_{H^j}^j(\cdot))(s-t)} ds \quad \text{(A.5)}$$

Substituting Eq. (A.5) into Eq. (A.4) yields the following.

$$\begin{aligned}\dot{\mu}_t^j = &-(r^j - \alpha^j - k^j\psi_{H^j}^j(\cdot) - l^j\theta_{H^j}^j(\cdot))\int_t^\infty (C_{H^j}^j(\cdot) - \mu_t^i l^i \theta_{H^j}^i(\cdot)) e^{-(r^j-\alpha^j-k^j\psi_{H^j}^j(\cdot)-l^j\theta_{H^j}^j(\cdot))(s-t)} ds \\ &+ C_{H^j}^j(\cdot) - \mu_t^i l^i \theta_{H^j}^i(\cdot)\end{aligned} \quad \text{(A.6)}$$

Moreover, we analyze the slope of the optimal abatement path. To determine how abatement changes over time, we differentiate the first-order condition governing abatement with respect to t. In the first-best case, differentiating Eqs. (1) and (2) with respect to t, then by rearranging it, we obtain

$$\dot{A}_t^F = \frac{(1-\varepsilon)\dot{\tau}_t^F + \varepsilon\dot{\tau}_t^G + \dot{\mu}_t^F k^F \psi_A^F(\cdot) + (\psi_{AH}^F(\cdot)\mu_t^F k^F - C_{AH}^F(\cdot))\dot{H}_t^F}{C_{AA}^F(\cdot) - \mu_t^F k^F \psi_{AA}^F(\cdot)} \quad \text{(A.7)}$$

$$\dot{A}_t^G = \frac{\dot{\tau}_t^G + \dot{\mu}_t^G k^G \psi_A^G(\cdot) + (\psi_{AH}^G(\cdot)\mu_t^G k^G - C_{AH}^G(\cdot))\dot{H}_t^G}{C_{AA}^G(\cdot) - \mu_t^G k^G \psi_{AA}^G(\cdot)} \quad \text{(A.8)}$$

If we consider an ITC scenario in which $k^G = 0$, we obtain the following equation:

$$\dot{A}_t^G = \frac{\dot{\tau}_t^G - C_{AH}^G(\cdot)\dot{H}_t^G}{C_{AA}^G(\cdot)} \qquad \text{(A.9)}$$

For the optimality case in each region, we obtain the same outcome for region G. Differentiating Eq. (15) with respect to t, and rearranging it, we obtain,

$$\dot{A}_t^F = \frac{(1-\varepsilon)\dot{\tau}_t^F + \dot{\mu}_t^F k^F \psi_A^F(\cdot) + (\psi_{AH}^F(\cdot)\mu_t^F k^F - C_{AH}^F(\cdot))\dot{H}_t^F}{C_{AA}^F(\cdot) - \mu_t^F k^F \psi_{AA}^F(\cdot)} \qquad \text{(A.10)}$$

Finally, we examine the slope of the optimal emission tax. Let us assume that $k^F = 1$, $\varphi^F = 0$ and $k^G = 0$. Differentiating Eqs. (22) and (23) with respect to t, we obtain the following:

$$\dot{t}_t^F = (1-\varepsilon)\dot{\tau}_t^F + \varepsilon\dot{\tau}_t^G + \dot{\mu}_t^F \psi_A^F(\cdot) + \mu_t^F \psi_{AA}^F(\cdot)\dot{A}_t^F + \mu_t^F \psi_{AH}^F(\cdot)\dot{H}_t^F \qquad \text{(A.11)}$$

$$\dot{t}_t^G = \dot{\tau}_t^G. \qquad \text{(A.12)}$$

For individual region optimality case, we obtain the same result for region G. For region F,

$$\dot{t}_t^F = (1-\varepsilon)\dot{\tau}_t^F + \dot{\mu}_t^F \psi_A^F(\cdot) + \mu_t^F \psi_{AA}^F(\cdot)\dot{A}_t^F + \mu_t^F \psi_{AH}^F(\cdot)\dot{H}_t^F \qquad \text{(A.13)}$$

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