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Technological Change and International Interaction in Environmental Policies*

Yuichi Furukawa† and Yasuhiro Takarada‡

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Abstract

This paper considers the impact of differences in endogenous technological change between two countries on global pollution emissions under international strategic interaction in environmental policies. First, we demonstrate that an environmentally lagging country's technology may continue to advance through a learning-by-doing effect until it exceeds the environmental friendliness of a leading country that initially had the cleanest technology (i.e., environmental leapfrogging could occur). Whether a country eventually becomes an environmentally leading country depends on the country size and its awareness of environmental quality. Second, we find that global emissions fluctuate despite the fact that environmental technology advances in both countries. Global emissions eventually become constant because both countries cease to tighten environmental regulations when their technologies are sufficiently clean. The final emissions might be larger than emissions in early stages of adjustment under dirty technologies. If environmental leapfrogging frequently occurs, both countries possess similarly clean technologies, thereby reducing long-term global pollution.

JEL Classification Numbers: O30, O31, O33, O44, Q55

Keywords: Environmental policy, leapfrogging, learning-by-doing, strategic interaction, technological change, transboundary pollution

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1 Introduction

In order to control and limit climate change, long-term greenhouse gas emissions need to be reduced.[1] Given that alternative energy sources to fossil fuels, such as photovoltaic and wind power, are currently available at high cost, technological progress will be a key component of the long-term strategy to mitigate global greenhouse gas emissions without compromising economic growth.[2] Although developed countries have been responsible for most of the greenhouse gas emissions historically, in the coming decades, increasing emissions will be mainly caused by economic growth in developing countries (IPCC, 2007; OECD, 2012). It is argued that by leapfrogging straight to clean production paradigms, developing countries may be able to bypass the dirty stages of industrial growth experienced in the past by today's developed countries (IPCC, 2007; World Bank, 2003). Existing empirical evidence indicates that environmental leapfrogging in developing countries is possible provided a number of basic conditions are met (e.g., absorptive capacity, technology transfer, and environmental policy) and the key factors for success are different in each case.[3]

The purpose of this paper is to clarify the basic mechanism of the development and adoption of new clean technologies in the long-run in a two-country framework. In particular, we focus on how environmental leapfrogging occurs and affects global pollution emissions. Each country's environmental policy plays a critical role in technological change. Adoption of clean technologies induced by environmental policy in one country may reduce the other country's incentive for strict environmental policy that leads to development of new clean technologies. In other words, strategic interaction between countries might hamper long-term technological progress, which has a negative impact on the environment. Therefore, it is quite important to elucidate how endogenous technological change is affected by strategic environmental regulations and how differences in environmental technologies between countries affect global emissions. However, to our knowledge, there exist no theoretical models rigorously dealing with endogenous technological change under the presence of international strategic interaction.

We present a simple two-country model to consider the difference in countries' response in terms of adoption of new clean technologies to environmental policies. A unique final good generates transboundary pollution (greenhouse gas) as a by-product of production. In order to mitigate pollution damage, the national government requires each domestic firm to reduce its emissions. We identify and interpret the fundamental forces for technological progress in a Nash equilibrium of the policy game.

Our model highlights the impact of environmental regulations on endogenous technologi-

[1] According to Organisation for Economic Co-operation and Development (OECD) (2012), without new policies, by 2050, global greenhouse gas emissions will increase by more than 50% compared with the 2010 emissions, primarily due to a 70% growth in energy-related CO2 emissions. As a result, the average global temperature is projected to be 3-C to 6-C higher than preindustrial levels by the end of the century, which exceeds the globally agreed goal of limiting it to 2-C to prevent disruptive climate change. See also Intergovernmental Panel on Climate Change (IPCC) (2008).

[2] See, e.g., IPCC (2011) on renewable energy sources.

[3] See, for instance, Dasgupta et al. (2002) and Walz (2010) on a downward shift of the environmental Kuznets curve (EKC), Gallagher (2006) on energy-technology leapfrogging in the Chinese automobile industry, Huber (2008) who reviews the global diffusion of environmental innovations, Perkins (2003) who reviews environmental leapfrogging in developing countries, Watson and Sauter (2011) who review case studies of leapfrogging (e.g., the Korean steel industry, the Indian and Chinese wind industries, and bioethanol production in Brazil).

cal change in the long run.[4] As long as a country reduces pollutants, it learns how to produce in an environmentally friendly manner at low cost. Learning-by-doing determines whether a country has cleaner technologies than another country in the long run. This learning process is supported by existing empirical evidence that an increase in energy prices and environmental regulations not only reduces greenhouse gas emissions by shifting behavior away from polluting activities, but also encourages environmentally friendly innovation, which makes pollution control less costly in the long run (Newell et al., 1999; Popp, 2002).

Two important results of this paper are as follows. First, we demonstrate that environmental leapfrogging occurs under plausible conditions. As each country is assumed to regulate its emissions to maximize individual welfare, a country that initially has a dirty technology (an environmentally lagging country) tends to implement a stringent environmental policy. As a result, learning-by-doing effects are large in the lagging country and its technology becomes environmentally friendly more rapidly than the other country that initially had a clean technology (an environmentally leading country). Thus, the lagging country's environmental friendliness could continue to increase until it exceeds the leading country's environmental friendliness. Each country's friendliness converges to a certain level in the long run because the government ceases to implement environmental regulations when its technology is sufficiently clean. We can show that whether a country eventually becomes an environmentally leading country depends on country size and awareness of environmental quality.

Second, we find the striking result that global pollution emissions may fluctuate despite the fact that environmental technology monotonically advances in both countries. Global pollution emissions eventually become constant because both countries cease to tighten environmental regulations when their technologies are sufficiently clean. Surprisingly, however, the final constant amount of emissions might be higher than the emissions in early stages of adjustment under dirty technologies. In particular, if environmental leapfrogging frequently occurs, long-term global pollution is likely to be lower than the initial level.

The reason for this counterintuitive result is as follows. In our model, the technology in the lagging country advances more rapidly than that in the leading country. This feature implies that technologies in the two countries advance considerably if both countries experience a state of environmental lagging for many periods. That is, both countries possess similarly clean technologies because leapfrogging occurs more frequently. This is why the long-term level of global pollution can become low in the presence of leapfrogging. However, when leapfrogging does not occur, the two countries will have different environmental technologies in the long run. Under imbalanced technological progress, technological change is not enough to reduce global pollution.

Our results suggest the importance of balanced technological change. Most of the world's research and development (R&D) for environmental innovation occurs in high-income countries (e.g., Lanjouw and Mody, 1996). Dechezleprêtre et al. (2011) did find climate-friendly innovations in emerging Economies, but these innovations are limited. While international transfers of climate-mitigation technologies occur mostly between developed countries, technology transfers from developed countries to emerging countries are few in number, but have

[4] We follow the endogenous growth model of Romer (1986) by assuming the learning-by-doing effect in production activities. In this paper, we consider, in particular, the learning effect on advances in environmental technology.

been rising rapidly in recent years.[5] We need to accelerate international transfers to mitigate the imbalanced technological change between countries that could cause undesirable effects on the environment.

This paper is closely related to the literature on the interactions between environmental regulations and endogenous technological change through R&D and learning-by-doing. Bovenberg and Smulders (1996) examined the link between tighter environmental policy and economic growth when the environmental R&D sector endogenously develops abatement technologies. Goulder and Mathai (2000) explored policy-induced technological change for the design of carbon-abatement policies when the channels of technological progress are based on R&D and learning-by-doing. Acemoglu et al. (2012) considered whether research can be directed to improving the productivity of clean and dirty intermediate goods sectors and showed that sustainable long-run growth can be achieved with temporary taxation of dirty innovation and production when the inputs are sufficiently substitutable. Bosetti et al. (2008) and Fischer and Newell (2008) empirically assessed the effects of technological progress through learning, R&D, and knowledge spillovers. None of these studies developed a two-country model to study the strategic interaction of environmental policies between countries and the role of environmental leapfrogging. Our contribution is to clarify the interaction of endogenous technological change between countries.[6]

We also contribute to the international economics literature on leapfrogging. After Brezis et al. (1993) found the fundamental mechanism through which leapfrogging occurs in a simple Ricardian trade model with learning, various papers followed and identified the driving forces of leapfrogging, which include comparative (dis)advantage, international capital flows, and knowledge spillovers (Ohyama and Jones, 1995; Motta et al., 1997; Brezis and Tsiddon, 1998; van de Klundert and Smulders, 2001; Desmet, 2002).[7] The present paper contributes to this literature by considering leapfrogging in "environmental" leadership, while those papers do not address any environmental factors such as pollution emissions or environmental policies. Our paper is also new to the literature in finding a policy-based mechanism of leapfrogging. We demonstrate that environmental leapfrogging may result from a policy game between governments with strategic interactions in global emissions. In this sense, the leapfrogging in our model is not only a technology-driven phenomenon, but also a policy-driven phenomenon. In the literature, such policy-driven leapfrogging is not addressed.

The rest of the article is organized as follows. Section 2 introduces our model of endogenous technological change. Section 3 considers a Nash equilibrium of the policy game. Section 4 explores a key mechanism underlying environmental leapfrogging. Section 5 investigates the impact of leapfrogging on global pollution emissions and Section 6 concludes the article.

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[5] Popp (2012) provided a comprehensive review of the literature on environmentally friendly technological change and technology transfers.

[6] In the literature on trade and the environment, the interaction of environmental policy interventions is investigated using a two-country general equilibrium model, but technologies are exogenously given to focus on the effects of trade liberalization. See, e.g., Copeland and Taylor (2003).

[7] See Giovannetti (2001) for perpetual leapfrogging in a context of price competition between firms. In addition, some literature in the field of economic geography addresses both the theory and the empirical evidence of technological leapfrogging at regional level; see, for example, Quah (1996a, b).

2 Basic Model

Time is discrete extending from $t = 0$ to ∞. There are two countries, labeled by $i = A, B$. In the basic model, we keep the two countries as symmetric as possible. They differ only in initial environmental technological levels.[8] There is a single consumption good, which is taken as the numeraire. The consumption good is produced by perfectly competitive firms in both countries. There are constant returns to scale, and the technology converts one unit of (effective) labor into one unit of a good. The (gross) marginal cost in country i is thus equal to the wage rate, denoted as $w_i(t)$.

Industrial production emits pollutants. Assume that producing one unit of a good in country i generates $\kappa_i(t) > 0$ units of pollution. The variable $\kappa_i(t)$ captures how harmful the production technology in country i is to the environment. Therefore, $(\kappa_i(t))^{-1}$ is an indicator of environmental friendliness of the technology in country i.

In this paper, we use two different words concerning the environment. The first word is "awareness," to which we relate parameter ε. This captures how uncomfortable people feel about global pollutants. The second word is "friendliness," relating to $(\kappa_i(t))^{-1}$. This captures to what extent the production technology of a country generates pollution emissions.

In this study, we highlight the government's role in controlling emissions. In order to control the aggregate emission level, the national government of country i requires each domestic firm to reduce its pollution by $100\ \tau_i(t)$ %. We assume that every firm can reduce one unit of emission by hiring one unit of (effective) labor. The effective marginal cost for a firm to produce a unit of a good (with the inclusion of pollution reduction) is equal to $w_i(t)(1 + \kappa_i(t)\tau_i(t))$. We may relate this rate $\tau_i(t) \in [0, 1]$ to an environmental policy instrument; higher $\tau_i(t)$ implies a stricter environmental policy.

In each country, there is a representative consumer who inelastically supplies $L/2$ units of (effective) labor. The consumer in country i consumes $C_i(t)$ units of the single consumption good and is endowed with the following utility function:

$$u_i(t) = C_i(t) - \varepsilon \left(E_A(t) + E_B(t)\right)^2, \tag{1}$$

where $E_i(t)$ is the flow of pollution emission generated by country i and $\varepsilon > 0$ denotes the degree of environmental awareness.

We treat pollution as a flow although most environmental problems are stock ones. The reason is as follows. First, if the depreciation rate of the pollution stock is high (e.g., the natural rate of removal of atmospheric pollution is high), the flow assumption may be a reasonable approximation (e.g., Schou, 2002; Grimaud and Tournemaine, 2007). Second, it simplifies the analysis without altering the main insight of our paper.

3 Short-run Equilibrium

In this section, we will characterize the short-run equilibrium of our model. Although our model is very simple, its equilibrium behavior appears to be complex. To explain this, first,

[8] In Section 4.3, we will investigate the roles of heterogeneity between the countries.

we will see the consumers' and firms' optimal activities in market equilibrium. Then, we will characterize the governments' optimal environmental policy in a Nash equilibrium of the policy game played by the two countries.

3.1 Market Equilibrium

Under free trade, the effective marginal costs must be equated between the two countries. Thus we have $w_A(t)\left((1+\kappa_A(t)\tau_A(t)\right) = w_B(t)\left(1+\kappa_B(t)\tau_B(t)\right) = 1$. The equilibrium wages are obtained as

$$w_i(t) = \frac{1}{1+\kappa_i(t)\tau_i(t)}. \tag{2}$$

The labor market equilibrium conditions determine the equilibrium levels of national output equal to

$$Y_i(t) = \frac{L/2}{1+\kappa_i(t)\tau_i(t)}. \tag{3}$$

We thus obtain the indirect utility function as

$$u_i(t) = \frac{L/2}{1+\kappa_i(t)\tau_i(t)} - \varepsilon\left(\sum_{i\in\{A,B\}} E_i(t)\right)^2, \tag{4}$$

where the pollution is given by

$$E_i(t) = (1-\tau_i(t))\frac{L\kappa_i(t)/2}{1+\kappa_i(t)\tau_i(t)} \tag{5}$$

for $i = A$ and B.

3.2 Optimal Policy Equilibrium

The government in each country, say i, controls their environmental policy tool $\tau_i(t)$ so as to maximize utility, given their foreign policy $\tau_j(t)$. An environmental policy reaction function is defined as $\tau_i^*(t;\ \tau_j^*(t)) = \arg\max_{\tau_i(t)\in[0,1]} u_i(t)$. Solving this nonlinear optimization problem with (4) derives the environmental policy reaction function as

$$\tau_i^*(t;\tau_j^*(t)) = \begin{cases} 0 & \text{if } \varepsilon L \le \frac{1}{1+\kappa_i(t)}\left(\kappa_i(t) + \frac{\kappa_j(t)\left(1-\tau_j^*(t)\right)}{1+\kappa_j(t)\tau_j^*(t)}\right)^{-1} \\ e_i(t) & \text{otherwise} \\ 1 & \text{if } \varepsilon L \ge \frac{1}{1+\kappa_i(t)}\left(\frac{\kappa_j(t)\left(1-\tau_j^*(t)\right)}{1+\kappa_j(t)\tau_j^*(t)}\right)^{-1} \end{cases}, \tag{6}$$

where

$$e_i(t) = \frac{\varepsilon L - \frac{1}{\kappa_i(t)}\left(\frac{1}{1+\kappa_i(t)} - \frac{\kappa_j(t)\left(1-\tau_j^*(t)\right)}{1+\kappa_j(t)\tau_j^*(t)}\varepsilon L\right)}{\varepsilon L + \left(\frac{1}{1+\kappa_i(t)} - \frac{\kappa_j(t)\left(1-\tau_j^*(t)\right)}{1+\kappa_j(t)\tau_j^*(t)}\varepsilon L\right)}. \tag{7}$$

Equation (6) suggests a possibility of so-called carbon leakage. As $\tau_i^*(t, \tau_j^*(t))$ is globally a decreasing function in $\tau_j^*(t)$, the government of Country i responds to a tightened foreign environmental policy (an increase in $\tau_j(t)$) by weakening the domestic policy (a decrease in $\tau_i(t)$). Thus, a part of the emissions reduction in Country j may be offset by an increase in emissions in Country i. At the aggregate level, a tightening of the environmental policy in one country may increase global emissions, showing the possibility of carbon leakage.

Next let us think of a Nash equilibrium in the environmental policy game played between the two governments. Denote as $(\tau_A^*(t),\ \tau_B^*(t))$ a pair of policy strategies taken in the Nash equilibrium. This equilibrium pair of policies can be calculated as a solution to the system consisting of the two optimal policy equations: $\tau_A^*(t) = \tau_A^*(t, \tau_B^*(t))$ and $\tau_B^*(t) = \tau_B^*(t, \tau_A^*(t))$. To derive the equilibrium policies, first, it is useful to note two basic facts. First, $(\tau_A^*(t), \tau_B^*(t)) = (1, 1)$ and $(\tau_A^*(t), \tau_B^*(t)) = (e_A(t), e_B(t))$ cannot be Nash equilibria.[9] Second, if the world pollution level $\kappa_A(t) + \kappa_B(t)$ is sufficiently low, both countries do not adopt an environmental policy:

$$(\tau_A^*(t), \tau_B^*(t)) = (0, 0) \text{ if } \kappa_A(t) + \kappa_B(t) < \min_{i \in \{A,B\}} \left\{ \frac{1}{\varepsilon L \left(1 + \kappa_i(t)\right)} \right\}. \tag{8}$$

By using (6) and (7), we can easily obtain the equilibrium pair of the environmental policy in the following.[10] Define $\hat{\kappa}$ such that $\hat{\kappa} = 1/(\varepsilon L\,(1 + \hat{\kappa}))$. With $i \neq j$, the equilibrium policy pair is characterized by

$$(\tau_i^*(t), \tau_j^*(t)) = \begin{cases} (p_i(t), 0) & \text{if } \begin{array}{l} \min\left\{\kappa_i(t), \frac{1}{\varepsilon L(1+\kappa_i(t))}\right\} \\ \quad > \kappa_j(t) \geq \frac{1}{\varepsilon L(1+\kappa_i(t))} - \kappa_i(t) \end{array} \\ (1, 0) & \text{if } \hat{\kappa} > \kappa_j(t) > \frac{1}{\varepsilon L(1+\kappa_i(t))} \\ (1, q_j(t)) & \text{if } \kappa_i(t) > \kappa_j(t) \geq \hat{\kappa} \end{cases}, \tag{9}$$

where we define two functions in t, $p_i(t)$ and $q_j(t)$, that satisfy $0 < q_i(t) < p_j(t) < 1$. Formal definitions of these two functions are

$$p_i(t) \equiv \frac{\varepsilon L - \frac{1}{\kappa_i(t)}\left(\frac{1}{1+\kappa_i(t)} - \varepsilon L \kappa_j(t)\right)}{\varepsilon L + \left(\frac{1}{1+\kappa_i(t)} - \varepsilon L \kappa_j(t)\right)} \text{ and } q_j(t) \equiv \frac{\varepsilon L - \frac{1}{\kappa_j(t)} \frac{1}{1+\kappa_j(t)}}{\varepsilon L + \frac{1}{1+\kappa_j(t)}}. \tag{10}$$

By using (8) and (9) with (10), Figure 1 relates the environmental technologies of both countries, $(\kappa_A(t), \kappa_B(t))$, to their environmental equilibrium policies, $(\tau_A^*(t), \tau_B^*(t))$, in (8) and (9). These complex equations and figures simply imply that the country that has a dirtier technology (larger $\kappa_i(t)$) is more willing to impose stricter environmental restrictions (larger $\tau_i(t)$). We can formally prove the following fact.

Lemma 1 *A country with a less environmentally friendly technology tends to implement a stricter environmental policy in equilibrium;* $\tau_i^*(t) \geq \tau_j^*(t)$ *if* $\kappa_i(t) > \kappa_j(t)$.

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[9] The proof is as follows. Substituting $e_j(t)$ into $e_i(t)$ results in $\left(\frac{\tau_i^*(t)}{\kappa_i(t)} + 1\right)\left(\frac{\kappa_i(t)}{2\varepsilon(1+\kappa_i(t))} - \frac{\kappa_j(t)}{2\varepsilon(1+\kappa_j(t))}\right) = 0$. This does not hold in general because $\tau_i^*(t) > 0$.

[10] See Appendix A for detailed derivations.

4 Technological Leadership in the Environment

In this section, we will introduce an endogenous process through which the environmental technology in either country advances. We will demonstrate that the environmental technological progress in either country interacts with each other to result in international cycles in environmental technological leadership.

We provide a formal definition of environmental technological leadership and leapfrogging. Firstly, we define environmental technological leadership as the state whereby a given country has the most environmentally friendly technology among all countries. Thus, we refer to a country that has a lower $\kappa_i(t)$ as an environmentally leading country. A country with a higher $\kappa_i(t)$ is called an environmentally lagging country. We may say that "environmental leapfrogging" occurs if environmental leadership shifts between the countries, i.e., if $\kappa_i(t) < \kappa_j(t)$ changes to $\kappa_i(t+1) > \kappa_j(t+1)$ with $i \neq j$. Without loss of generality, we assume $\kappa_A(0) < \kappa_B(0)$ holds in period 0 (initial period). Country A is initially an environmentally leading country.

4.1 Learning-by-doing and Technological Progress

We incorporate endogenous environmental technological progress into the model by considering a learning-by-doing effect,[11] as in the endogenous growth literature (Romer, 1986). Our basic idea is that a country that reduces pollutants learns how to produce in an environmentally friendly manner.

Suppose

$$\kappa_i(t+1) = \kappa_i(t) - \eta_i(t), \tag{11}$$

through which the pollution level of technology $\kappa_i(t)$ decreases over time to the extent $\eta_i(t) \geq 0$. Then we assume that the decrease in pollution level $\eta_i(t)$ is a function of the pollutant reduction made by country i, $\tau_i^*(t)\kappa_i(t)Y_i(t)$; i.e., $\eta_i(t) = \eta(\tau_i^*(t)\kappa_i(t)Y_i(t), t)$. We put two natural assumptions on learning function η: (a) there is no advance if there is no environmental activity ($\eta(0,t) = 0$ for any $t \geq 0$); (b) in each period t, a firm that invests more in pollution reduction learns more on how to produce in an environmentally friendly manner ($\eta(z', t) > \eta(z, t)$ as $z' > z$ for any $t \geq 0$). It can be shown that, in equilibrium, $\tau_i^*(t)\kappa_i(t)Y_i(t)$ monotonically increases with $\tau_i^*(t)$; thus, we may rewrite the learning function as $\eta_i(t) = \eta(\tau_i^*(t), t)$, keeping the two assumptions (a) and (b) in function η.

With (11), we can determine the direction in which international environmental friendliness, $(\kappa_A(t), \kappa_B(t))$, advances over time. Figure 2 depicts a usual phase diagram, in which $\kappa_A(t)$ ($\kappa_B(t)$) is measured along the horizontal (vertical) axis. Note that the time index t is omitted in this figure.

As shown in Figure 2, there are three patterns of the direction in which $(\kappa_A(t), \kappa_B(t))$ moves over time. First, in the region of $(0,0)$, there are no technological advances in which both countries do not engage in the environmental (pollution-reducing) activity ($\tau_i^*(t) = 0$ for $i = A, B$). Here $(\kappa_A(t), \kappa_B(t))$ never moves and is stable. Second, in the regions of $(p_A, 0)$ and $(1, 0)$ ($(0, p_B)$ and $(0, 1)$), only country A (B) invests labor resources in the abatement.

[11] See Newell et al. (1999) and Popp (2002) for empirical evidence.

Therefore, only $\kappa_A(t)$ ($\kappa_B(t)$) decreases over time by assumption (a). This fact is indicated by the left arrow (down arrow) within those regions. Third, in the region of $(1, q_B)$ ($(q_A, 1)$), both countries make the environmental investment. As $\tau_A^*(t) > \tau_B^*(t)$ ($\tau_A^*(t) < \tau_B^*(t)$) holds, $\kappa_A(t)$ ($\kappa_B(t)$) decreases more sharply than $\kappa_B(t)$ ($\kappa_A(t)$) does because of assumption (b). This is indicated by the long left arrow and the shorter down arrow (the long down arrow and the shorter left arrow). A typical trajectory, starting from point K_0, is illustrated by dotted arrows in Figure 2.

4.2 Environmental Leapfrogging

Take an example path starting from K_0 in Figure 2, in which $\kappa_A(0) < \kappa_B(0)$. Along an equilibrium path from K_0, as can be shown by using the phase diagram, environmental leadership may shift between the two countries. At first, country A is the leader with lower $\kappa_A(t)$ and it retains its environmental leadership in the subsequent periods $1-4$. Along the equilibrium path, leapfrogging occurs in period 5; country B becomes a new environmental leader.

We can formally identify this possibility of environmental leapfrogging. Recall that by (9) and Figure 1, the equilibrium environmental policy pair is $(\tau_A^*(0), \tau_B^*(0)) = (0,0),\ (0, p_B(0))$, $(0,1)$, or $(q_A(0), 1)$. Define a new threshold value $\tilde{\kappa}$ such that $2\tilde{\kappa} = 1/(\varepsilon L\,(1+\tilde{\kappa}))$. See Figure 3. If an initial point exists in the blue region in Figure 3 (a), like point k_0, the environmental friendliness pair $(\kappa_A(t), \kappa_B(t))$ will eventually fall below the 45 degree line. The blue region is characterized by

$$\kappa_B(0) > \kappa_A(0) \in (\tilde{\kappa}, \hat{\kappa}). \tag{12}$$

See Figure 3 (b), in which the red region corresponds to

$$\kappa_B(0) > \kappa_A(0) \geq \hat{\kappa}. \tag{13}$$

If the pair $(\kappa_A(t), \kappa_B(t))$ exists such as k_0' in the red region in Figure 3 (b), it may eventually either fall below the 45 degree line or move to the blue region of (12). This is guaranteed by assuming that the extent of technological progress that takes place within a period is not too large, i.e., there exists some $\delta > 0$ such that $\eta(\cdot, t) < \delta$.[12] Given this assumption, if (13) holds, we can show that environmental leadership will eventually shift internationally.

Taking into account (12) and (13) with Lemma 1, we have our first result.

Proposition 1 (Environmental Leapfrogging) *Think of an environmentally leading country A and an environmentally lagging country B with $\kappa_A(0) < \kappa_B(0)$. If the extent of technological progress taking place within a period is not too large, so long as*

$$\kappa_A(0) > \tilde{\kappa}, \tag{14}$$

the environmental leadership initially retained by country A will eventually shift to the initial lagging country B; environmental leapfrogging takes place.

[12]If a step of technological progress was very large, $(\kappa_A(t), \kappa_B(t))$ might immediately jump into the grey region of $(0,0)$, in which case leapfrogging never takes place.

To determine our understanding of environmental policy from this result, let us review our result on a step-by-step basis. Initially, country A is an environmentally leading country with $\kappa_A(0) < \kappa_B(0)$. As the environmentally lagging country B is more polluting, it requires domestic firms to reduce pollutants more by adopting a stricter environmental policy, i.e., $\tau_B^*(0) > \tau_A^*(0)$ (Lemma 1). Through the learning process, the lagging country B's technology thus becomes environmentally friendly more rapidly than the leading country A's technology does. If the technology of the leading country A were initially environmentally friendly enough to satisfy $\kappa_A(0) < \tilde{\kappa}$, the world economy would get to the equilibrium without any environmental regulations ($\tau_i^*(t) = 0$). However, as the leading country A is initially not very environmentally friendly by (14), the lagging country's friendliness continues to increase until it exceeds the leading country's. Therefore, if (14) holds, the environmental leadership eventually shifts internationally.

What happens after the first environmental leapfrogging takes place? The answer to this question is that a second leapfrogging may follow the first. See Figure 2, in which K_5 moves horizontally in the subsequent period 6. Imagine that K_5 crosses the 45 degree line, so the technological leadership shifts internationally again in period 6. However, in the long run, leapfrogging necessarily ceases to exist because the world economy's friendliness pair $(\kappa_A(t), \kappa_B(t))$ eventually converges to the grey region in Figure 2, in which $(\tau_A^*(t), \tau_B^*(t)) = (0, 0)$ and $(\kappa_A(t), \kappa_B(t))$ stays constant. Denote by (κ_A^*, κ_B^*) the point that $(\kappa_A(t), \kappa_B(t))$ finally reaches in the grey region. Whether $\kappa_A^* > \kappa_B^*$ or $\kappa_A^* < \kappa_B^*$ is not determinate, depending in a complex fashion on the initial friendliness levels $(\kappa_A(0), \kappa_B(0))$. That is, which country ultimately becomes an environmentally leading country is indeterminate. This indeterminacy essentially comes from the symmetry between the countries (which differ only in $\kappa_i(t)$).

4.3 Which Country Prevails? The Role of Country Heterogeneity

So far, we have demonstrated that environmental leapfrogging may occur if the leading country's technology is initially not so environmentally friendly. So long as countries are essentially identical, in the analysis above, which country prevails is not determined. A fundamental question arises as to which country becomes the ultimate environmental leader in the long run. In this section, we will give an answer to this question by allowing for country heterogeneity.

Suppose that one country is relatively aware of the environment, say country A, and the other has a large amount of effective labor (i.e., population times their labor productivity), say country B. Denote as L_i and ε_i the effective labor and environmental awareness of country i, where $i = A, B$. Then, $\varepsilon_A \geq \varepsilon_B$ and $L_A \leq L_B$. Equilibrium optimal policies are shown in Figure 4. (See Appendix A for mathematical details.)

Figure 4 (a), by setting $\varepsilon_A = \varepsilon_B$ and $L_A < L_B$, shows how the difference in international effective labor sizes affects the equilibrium policies. Define $\hat{\kappa}_i$ such that $\hat{\kappa}_i = 1/(\varepsilon_i L_i (1 + \hat{\kappa}_i))$. Because $\hat{\kappa}_B$ is lower than $\hat{\kappa}_A$ in this case, the stable region $(0, 0)$ is twisted with a rightward bias. In fact, as L_B increases, $\hat{\kappa}_B$ decreases and $\hat{\kappa}_A$ increases. Therefore, when country B's effective labor L_B is very large, $\kappa_A > \kappa_B$ (where country B is the leader) holds almost everywhere in the stable region $(0, 0)$. Given that the world economy eventually moves into the stable region $(0, 0)$, we can say that a county with large effective labor is more likely to eventually obtain the environmental leadership ($\kappa_A > \kappa_B$).

Remark 1 *A country that has a large amount of effective labor tends to eventually become an environmental leader in the long run.*

The implication of Remark 1 is as follows. A large amount of effective labor implies a huge potential pollution emission. Thus, the government of country B would implement long-term environmental policy that promotes the technological progress as a by-product. Therefore, given its large effective labor, country B may tend to obtain environmental leadership eventually, even if it is initially an environmentally lagging country.

Heterogeneity of environmental awareness, $\varepsilon_A > \varepsilon_B$, determines which country finally retains the environmental leadership. See Figure 4 (b), with the definition of $\overline{\kappa}$ where $2\overline{\kappa}(1+\overline{\kappa}) \equiv 1/\varepsilon_A$, which means $\overline{\kappa} = \overline{\kappa}(\varepsilon^A)$ with $\overline{\kappa}'(\varepsilon^A) < 0$. Starting from any point in the red-box region (where $\kappa_B(t) < \overline{\kappa}$ and $\kappa_B(t) < \kappa_A(t)$), $\kappa_B(t) < \kappa_A(t)$ holds in the long run. Outside the red-box region, any path eventually converges to a state with $\kappa_B(t) > \kappa_A(t)$, where country A is the leading country. As, by $\overline{\kappa}'(\varepsilon^A) < 0$, the red-box region becomes smaller as ε^A increases, we have the following statement.

Remark 2 *A country that has greater awareness ε of the environment tends to become an environmental leader in the long run.*

The implication of Remark 2 is straightforward. Given its greater environmental awareness ε_A, country A is more likely to adopt a stricter environmental policy. It follows that the learning-by-doing effect works more actively in country A, which would advance environmental technology in country A faster (decreasing $\kappa_A(t)$ faster than $\kappa_B(t)$).

5 Global Pollution Dynamics

How does environmental leapfrogging affect global pollution dynamics? To answer this fundamental question, we assume that the two countries differ only in their technological friendliness; $\kappa_A(t) < \kappa_B(t)$. Using (5), (9), and (10), we will elaborate how global pollution, $E(t) = E_A(t) + E_B(t)$, changes over time in each stage of environmental development.

Stage I:

Consider an earlier stage of environmental technology development, in which both countries adopt an environmental policy, $(\tau_A^*(t), \tau_B^*(t)) = (q_A(t), 1)$. In this case, as shown in the phase diagram in Figure 2, environmental technology advances in both countries; both $\kappa_A(t)$ and $\kappa_B(t)$ decreases over time. By (5), (9), and (10), we have

$$E(t) = \frac{1}{2\varepsilon\left(1+\kappa_A(t)\right)} \equiv e_A^1(t) \text{ as } \frac{1}{\varepsilon L(1+\kappa_A(t))} < \kappa_A(t) \ . \qquad (15)$$

Surprisingly, we find that, during this early stage (stage I), global pollution increases as environmental technologies in the leading country advance. That is, $E(t)$ increases as $\kappa_A(t)$ decreases.

Stage II:

The second stage is with $(\tau_A^*(t), \tau_B^*(t)) = (0, 1)$, where, as shown in Figure 2, technological progress takes place only for the lagging country. Only $\kappa_B(t)$ decreases over time. Global emissions in this case can be calculated as

$$E(t) = \frac{\kappa_A(t)L}{2} \equiv e_A^2(t) \text{ as } \frac{1}{\varepsilon L(1+\kappa_B(t))} < \kappa_A(t) < \frac{1}{\varepsilon L(1+\kappa_A(t))} . \quad (16)$$

While the leading country generates a constant amount of pollution, the lagging country reduces all of its pollution emissions. Therefore, it is clear that global pollution is kept constant. That is, $E(t)$ never changes while $\kappa_B(t)$ decreases over time.

A fundamental question is whether global pollution rises or declines in the period of regime switching from stages I to II. The answer is not clear and global pollution depends on the extent of technological progress that takes place within that period. Suppose that regime switching from stage I to II occurs from periods t to $t+1$. If the extent of technological progress in the leading country, i.e., $\eta_A(t)$, is reasonably large, global pollution may be reduced with this regime switching; $E(t+1) < E(t)$ may hold.[13]

Stage III:

Next, think of a more advanced stage of environmental technology development with $(\tau_A^*(t), \tau_B^*(t)) = (0, p_B(t))$. In this case, as in stage II, only $\kappa_B(t)$ decreases over time. We can obtain

$$E(t) = \frac{1}{2\varepsilon\left(1+\kappa_B(t)\right)} \equiv e_A^3(t) \text{ as } \kappa_A(t) < \frac{1}{\varepsilon L(1+\kappa_B(t))} < \kappa_A(t) + \kappa_B(t) \; ; \quad (17)$$

global emissions start to increase again. In a regime switch from stages II to III, global pollution necessarily increases.[14]

Stage IV:

Finally, if both countries have a sufficiently clean technology such that if $\kappa_A(t) + \kappa_B(t) < \frac{1}{\varepsilon L(1+\kappa_B(t))}$, they do not need environmental regulation; $(\tau_A^*(t), \tau_B^*(t)) = (0, 0)$. In this case, global pollution is given by

$$E(t) = \frac{\left(\kappa_A(t) + \kappa_B(t)\right)L}{2} \equiv e^4(t) \text{ as } \kappa_A(t) + \kappa_B(t) < \frac{1}{\varepsilon L(1+\kappa_B(t))} \; ; \quad (18)$$

global pollution emissions are constant. In a regime switch from stages III to IV, using a simple numerical example, we can show that global emissions can be reduced if technological progress for the lagging country, $\eta_B(t)$, is reasonably large.

Consequently we have the following proposition.

Proposition 2 (Global Pollution) *In the process of environmental technological progress, global pollution $E(t)$ may fluctuate over time and eventually stays at $\left(\kappa_A(t) + \kappa_B(t)\right)L/2$.*

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[13] To verify this, consider a numerical example with $L = 0.5$ and $\varepsilon = 0.5$. Assume $(\kappa_A(t), \kappa_B(t)) = (1.75, 4.5)$ and $(\kappa_A(t+1), \kappa_B(t+1)) = (1, 3.5)$. Then, regime switching occurs from t to $t+1$, noting (15) and (16). Furthermore, $E(t) = 0.36364$ declines to $E(t+1) = 0.25$.

[14] Suppose that the world goes from stages II to III in periods $t+1$ to $t+2$. By (16) and (17), noting $\kappa_A(t+1) = \kappa_A(t+2)$ in stage II, we can easily verify $E(t+1) < E(t+2)$.

To explore the global pollution dynamics in detail, we consider two numerical examples that, respectively, capture the typical trajectories of global pollution, $\{E(t)\}$.[15] We take $\varepsilon = L = 0.5$ and think of $(\kappa_A(t-1), \kappa_B(t-1)) = (2.5, 7.5)$ as an initial state.

In the first example, (a), we assume that technological progress follows $(\eta_i(t), \eta_k(t)) = (2, 0.75)$ if $\tau_i^*(t) > \tau_k^*(t) > 0$ and $(2, 0)$ if $\tau_i^*(t) > \tau_k^*(t) = 0$, which is consistent with the learning rules that we assume. The complete path of global pollution $E(t)$ is illustrated in Figure 5 (a). In period $t-1$, $(\kappa_A(t-1), \kappa_B(t-1)) = (2.5, 7.5)$ satisfies the inequality condition in (15), so that the world economy is in the earliest stage I, where $(\tau_A^*(t-1), \tau_B^*(t-1)) = (q_A(t), 1)$. By (15), global pollution is $E(t-1) \simeq 0.28571$. According to the above simple process of technological progress, environmental friendliness improves for both the leading and the lagging countries: $(\kappa_A(t), \kappa_B(t)) = (1.75, 5.5)$ holds in period t, in which the inequality condition in (15) still holds (stage I). Then, global pollution increases to $E(t) \simeq 0.36364$. By analogous calculations, we can characterize an entire trajectory for this example: $E(t+1) = 0.25$ in stage II, $E(t+2) = 0.4$ in stage III, and $E(t+3) = 0.375$ in stage IV with $(\kappa_A(t+3), \kappa_B(t+3)) = (1, 0.5)$. In this example without leapfrogging, global emissions fluctuates and eventually increases up to 0.375, which is higher than the initial level (0.28571).

We then consider another example, (b), in which leapfrogging plays a role. It differs from example (a) only in that technological progress is slower: $(\eta_i(t), \eta_k(t)) = (1, 0.3)$ if $\tau_i^*(t) > \tau_k^*(t) > 0$ and $(1, 0)$ if $\tau_i^*(t) > \tau_k^*(t) = 0$, which is also consistent with the learning rules that we assume. The entire path is depicted in Figure 5 (b). In period $t-1$, the world economy is in stage I where country A is the leading country, and $E(t-1) \simeq 0.28571$. Then, global pollution monotonically increases in stage I up to period $t+2$. In the subsequent periods, $t+3$ and $t+4$, the world economy shifts to stage II with a small decrease in pollution, $E(t+3) = E(t+4) = 0.325$. Next, in period $t+5$, stage III occurs and pollution increases to $E(t+5) = 0.4$. In period $t+6$, leapfrogging occurs; country B becomes a new leading country with $(\kappa_A(t+6), \kappa_B(t+6)) = (1.3, 0.5)$. While leapfrogging occurs, the world economy is still in stage III and pollution continues to increase to $E(t+6) = 0.43478$. In period $t+7$, $(\kappa_A(t+7), \kappa_B(t+7)) = (0.3, 0.5)$ follows; leapfrogging occurs again and stage IV occurs in period $t+7$, in which country A gets the leadership back and global pollution sharply decreases down to $E(t+7) = 0.2$ through regime switching to stage IV. In this example with leapfrogging, global pollution fluctuates at first, but finally declines to the lowest level (0.2).

These two examples suggest that global pollution is likely to decline through leapfrogging in the long run. This is essentially because, in our model, the technology in the lagging country advances more rapidly than that in the leading country as a result of the policy game with international strategic interactions. Technologies in the two countries advance considerably and similarly if both countries experience the state of a lagging country for more periods. This implies that technological progress may be more balanced between the two countries as leapfrogging occurs more frequently. In that sense, environmental leapfrogging may lead to more balanced technological progress in the world, thereby reducing global pollution in the long run.

A striking feature of this result is that global pollution emissions may fluctuate despite the fact that environmental technology monotonically advances in both countries. The intuition

[15] See Appendix B for detailed calculations.

behind the result is as follows. Changes in pollution can be decomposed into two fundamental forces: scale and technique effects.[16] Strict environmental policy in the early stage of environmental technology development induces rapid technological progress, which reduces pollution (the technique effect). As technological change is external to the economy, the government implements a too-strict environmental policy in the early stage compared with the case where technological change is internalized. The government will mitigate environmental policy after it discovers technological progress. That is, the technique effect becomes small as time proceeds. As technological progress enables a country to save labor input used for abatement activity, more labor can be employed in production of the good. This causes an increase in pollution (the scale effect). The scale effect decreases as technological progress becomes slow.

Given that the scale effect dominates, an increase in global pollution over time implies that production increases over time. We can easily verify that in terms of utility, the increase in the output dominates the increase in pollution. As environmental technology improves, utility increases over time. This would suggest an important role for a nice balance of production (economic growth) and the environment.

Proposition 2 may suggest that the scale effect in some cases plays a dominant role in the real-world economy, where environmental technology advances, but emissions also increase. In other words, the real world is still in intermediate stages, I–III, in which pollution emissions never decrease without regime switching. Given this, our result predicts that the observed emission expansion in the world economy, together with the output increase, may stop eventually if regime switching occurs, i.e., if the environmental technology becomes sufficiently clean and the world economy goes to the final stage, IV, as in example (b).

Our model may explain the underlying cause of the EKC. The EKC is a hypothesized inverted U-shaped relation between environmental quality and economic development.[17] In our model, production will increase over time because environmental technology advances through learning-by-doing effects. Our results shown in Figure 5 suggest that there is an inverted U-shaped relationship between pollution and time (or economic growth) if environmental leapfrogging occurs frequently. That is, balanced technological progress between countries could be a key factor for the EKC relationship in the world economy.

6 Concluding Remarks

In this paper, we constructed a simple two-country model with global pollution and endogenous technological progress induced by learning-by-doing. We characterized the structure of equilibria and the dynamic environmental policies that achieve technological progress or leapfrogging. Long-term global emissions and the dynamic path of environmental friendliness are related to the initial environmental friendliness, environmental awareness, and learning process between countries. Our findings underscore the importance of considering the implications of technological progress in a multicountry framework.

[16]This approach was initially used by Grossman and Krueger (1993). The scale effect measures the increase in pollution that would be generated if the economy was simply scaled up, holding all else constant. The technique effect captures reduction in pollution caused by a fall in emissions intensity, holding all else constant.

[17]See, for example, Dinda (2004) and Stern (2004) for a survey based on the EKC hypothesis.

The important implications of our results are as follows. (i) Leapfrogging may occur under reasonable conditions. Countries are likely to possess similar clean technologies in the long run when leapfrogging occurs frequently. (ii) A country that has a large amount of effective labor and/or considerable environmental awareness tends to eventually be an environmental leader in the long run. (iii) Imbalanced adoption of new clean technologies among countries is not always good for the environment. Global emissions can be mitigated by controlling technological change to be uniform between countries. This needs to have international coordination such as technology transfers and capacity building.

We have built a simple general equilibrium model to shed some light on the issue of development and adoption of new clean technologies to control global emissions. It is certainly worthwhile to build alternative models to more deeply understand the mechanism underlying international differences in technological progress. The following are in particular worth mentioning and have been left for future research. First, our analysis does not consider dynamic optimization because we treat pollution as a flow to derive clear-cut results. However, it is interesting to investigate the issue when pollution is a stock variable. Second, technological progress might be reinforced if the national government considers not only negative externalities caused by pollution, but also positive externalities of learning-by-doing. Third, the channel for knowledge growth could be by R&D investments as well as learning-by-doing. Last, there is no terms-of-trade effect because we have used a one-good model. Environmental regulations are affected by terms-of-trade effects, which could change the long-term pace of technological progress.

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Appendix A

The case with homogeneous countries. Assume $\kappa_i(t) > \kappa_j(t)$. By substituting $(\tau_i^*(t), \tau_i^*(t)) = (e_i(t), 0)$ and $(\tau_A^*(t), \tau_B^*(t)) = (1, e_j(t))$ into (6) and (7), we have

$$e_i(t) = \frac{\varepsilon L - \frac{1}{\kappa_i(t)}\left(\frac{1}{1+\kappa_i(t)} - \varepsilon L \kappa_j(t)\right)}{\varepsilon L + \left(\frac{1}{1+\kappa_i(t)} - \varepsilon L \kappa_j(t)\right)} \tag{A1}$$

and

$$e_j(t) = \frac{\varepsilon L - \frac{1}{\kappa_j(t)}\frac{1}{1+\kappa_j(t)}}{\varepsilon L + \frac{1}{1+\kappa_j(t)}}, \tag{A2}$$

respectively. With (A1) and (A2), noting $0 \leq e_i(t) \leq 1$ and $0 \leq e_j(t) \leq 1$ would imply (9), given the definitions of $p_i(t)$ and $q_i(t)$.

The case with heterogeneous countries. The reaction function becomes

$$\tau_i^*(t; \tau_j^*(t)) = \begin{cases} 0 & \text{if } \varepsilon_i \leq \frac{1}{1+\kappa_i(t)}\left(\kappa_i(t)L_i + \frac{\kappa_j(t)\left(1-\tau_j^*(t)\right)}{1+\kappa_j(t)\tau_j^*(t)}L_j\right)^{-1} \\ e_i(t) & \text{otherwise} \\ 1 & \text{if } \varepsilon_i \geq \frac{1}{1+\kappa_i(t)}\left(\frac{\kappa_j(t)\left(1-\tau_j^*(t)\right)}{1+\kappa_j(t)\tau_j^*(t)}L_j\right)^{-1} \end{cases}, \tag{A3}$$

where

$$e_i(t) = \frac{\varepsilon_i L_i - \frac{1}{\kappa_i(t)}\left(\frac{1}{1+\kappa_i(t)} - \frac{\kappa_j(t)\left(1-\tau_j^*(t)\right)}{1+\kappa_j(t)\tau_j^*(t)}\varepsilon_i L_j\right)}{\varepsilon_i L_i + \left(\frac{1}{1+\kappa_i(t)} - \frac{\kappa_j(t)\left(1-\tau_j^*(t)\right)}{1+\kappa_j(t)\tau_j^*(t)}\varepsilon_i L_j\right)}. \tag{A4}$$

Define $\hat{\kappa}_i$ such that $\hat{\kappa}_i \equiv \frac{1}{\varepsilon_i L_i(1+\hat{\kappa}_i)}$. Then, using (A3) and (A4), the equilibrium policy pair goes to

$$(\tau_i^*(t), \tau_j^*(t)) = \begin{cases} (0,0) & \text{if } \kappa_A(t)L_A + \kappa_B(t)L_B \leq \min_{i\in\{A,B\}}\left\{\frac{1}{\varepsilon_i(1+\kappa_i(t))}\right\} \\ (p_i(t), 0) & \text{if } \begin{array}{c}\min\left\{\frac{\varepsilon_i}{\varepsilon_j}\left(\kappa_i(t) + \frac{\varepsilon_i - \varepsilon_j}{\varepsilon_i}\right), \frac{1}{\varepsilon_i L_j(1+\kappa_i(t))}\right\} \\ > \kappa_j(t) \geq \frac{1}{\varepsilon_i L_j(1+\kappa_i(t))} - \kappa_i(t)\frac{L_i}{L_j}\end{array} \\ (1,0) & \text{if } \hat{\kappa}_j > \kappa_j(t) > \frac{1}{\varepsilon_i L_j(1+\kappa_i(t))} \\ (1, q_j(t)) & \text{if } \frac{\varepsilon_i}{\varepsilon_j}\left(\kappa_i(t) + \frac{\varepsilon_i - \varepsilon_j}{\varepsilon_i}\right) > \kappa_j(t) \geq \hat{\kappa}_j \end{cases}, \tag{A5}$$

where

$$p_i(t) = \frac{\varepsilon_i L_i - \frac{1}{\kappa_i(t)}\left(\frac{1}{1+\kappa_i(t)} - \kappa_j(t)\varepsilon_i L_j\right)}{\varepsilon_i L_i + \left(\frac{1}{1+\kappa_i(t)} - \kappa_j(t)\varepsilon_i L_j\right)} \text{ and } q_i(t) = \frac{\varepsilon_i L_i - \frac{1}{\kappa_i(t)}\frac{1}{1+\kappa_i(t)}}{\varepsilon_i L_i + \frac{1}{1+\kappa_i(t)}}. \tag{A6}$$

It is straightforward to illustrate Figure 4 by using the above equilibrium conditions.

Appendix B

In both examples, we think of $(\kappa_A(t-1), \kappa_B(t-1)) = (2.5, 7.5)$ as an initial point. Set $\varepsilon = L = 0.5$.

Example (a): Technological progress follows $(\eta_i(t), \eta_k(t)) = (2, 0.75)$ if $\tau_i^*(t) > \tau_k^*(t) > 0$ with $(2, 0)$ if $\tau_i^*(t) > \tau_k^*(t) = 0$, which is consistent with the learning rules that we assume.

As $(\kappa_A(t-1), \kappa_B(t-1)) = (2.5, 7.5)$, the world is in stage I by (15), and $E(t-1) = \frac{1}{1+2.5} \simeq 0.28571$. Given the values of $\eta_i(t)$ assumed, it goes to $(\kappa_A(t), \kappa_B(t)) = (1.75, 5.5)$. By (15), the world is also in stage I and we have $E(t) = \frac{1}{1+1.75} \simeq 0.36364$. In the subsequent period $t+1$, it becomes $(\kappa_A(t+1), \kappa_B(t+1)) = (1, 3.5)$. Noting (16), the world shifts to stage II in period $t+1$. We can calculate $E(t+1) = 0.25$. Next, $(\kappa_A(t+2), \kappa_B(t+2)) = (1, 1.5)$ satisfies the inequality condition in (17), so it is in stage III and $E(t+2) = \frac{1}{1+1.5} = 0.4$. Finally, it goes to $(\kappa_A(t+3), \kappa_B(t+3)) = (1, 0.5)$, which satisfies (18). In period $t+3$, the world moves to the terminal stage IV and we can calculate $E(t+3) = \frac{1.5}{4} = 0.375$.

Example (b): Technological progress follows $(\eta_i(t), \eta_k(t)) = (1, 0.3)$ if $\tau_i^*(t) > \tau_k^*(t) > 0$ and $(1, 0)$ if $\tau_i^*(t) > \tau_k^*(t) = 0$, which is consistent with the learning rules that we assume.

Note that $(\kappa_A(t-1), \kappa_B(t-1)) = (2.5, 7.5)$ ensures stage I for country A as a leading country, noting (15). We calculate $E(t-1) = \frac{1}{1+2.5} \simeq 0.28571$. Then, through the assumed process of technological progress, stage I continues in periods t to $t+2$: $(\kappa_A(t), \kappa_B(t)) = (2.2, 6.5)$, $(\kappa_A(t+1), \kappa_B(t+1)) = (1.9, 5.5)$, and $(\kappa_A(t+2), \kappa_B(t+2)) = (1.6, 4.5)$ while $E(t) = \frac{1}{1+2.2} \simeq 0.3125$, $E(t+1) = \frac{1}{1+1.9} \simeq 0.34483$, and $E(t+2) = \frac{1}{1+1.6} \simeq 0.38462$. In periods $t+3$ and $t+4$, it goes to $(1.3, 3.5)$ and then $(1.3, 2.5)$, in which case the world is in stage II noting (16). Then $E(t+3) = E(t+4) = \frac{1.3}{4} = 0.325$. Next, $(\kappa_A(t+5), \kappa_B(t+5)) = (1.3, 1.5)$, which satisfies (17). It is stage III and $E(t+5) = \frac{1}{1+1.5} = 0.4$. In period $t+6$, it goes to $(1.3, 0.5)$, in which leapfrogging occurs and Country B is a new leading country. An analogous inequality to that in (17), $\kappa_B(t) < \frac{1}{\varepsilon L(1+\kappa_A(t))} < \kappa_A(t)+\kappa_B(t)$, is satisfied, so that the world is in stage III, $E(t+6) = \frac{1}{1+1.3} = 0.43478$. Finally, it goes to $(\kappa_A(t+7), \kappa_B(t+7)) = (0.3, 0.5)$, in which leapfrogging occurs again. Country A regains the leadership and it satisfies (18), stage IV. Then we calculate $E(t+7) = \frac{0.8}{4} = 0.2$.

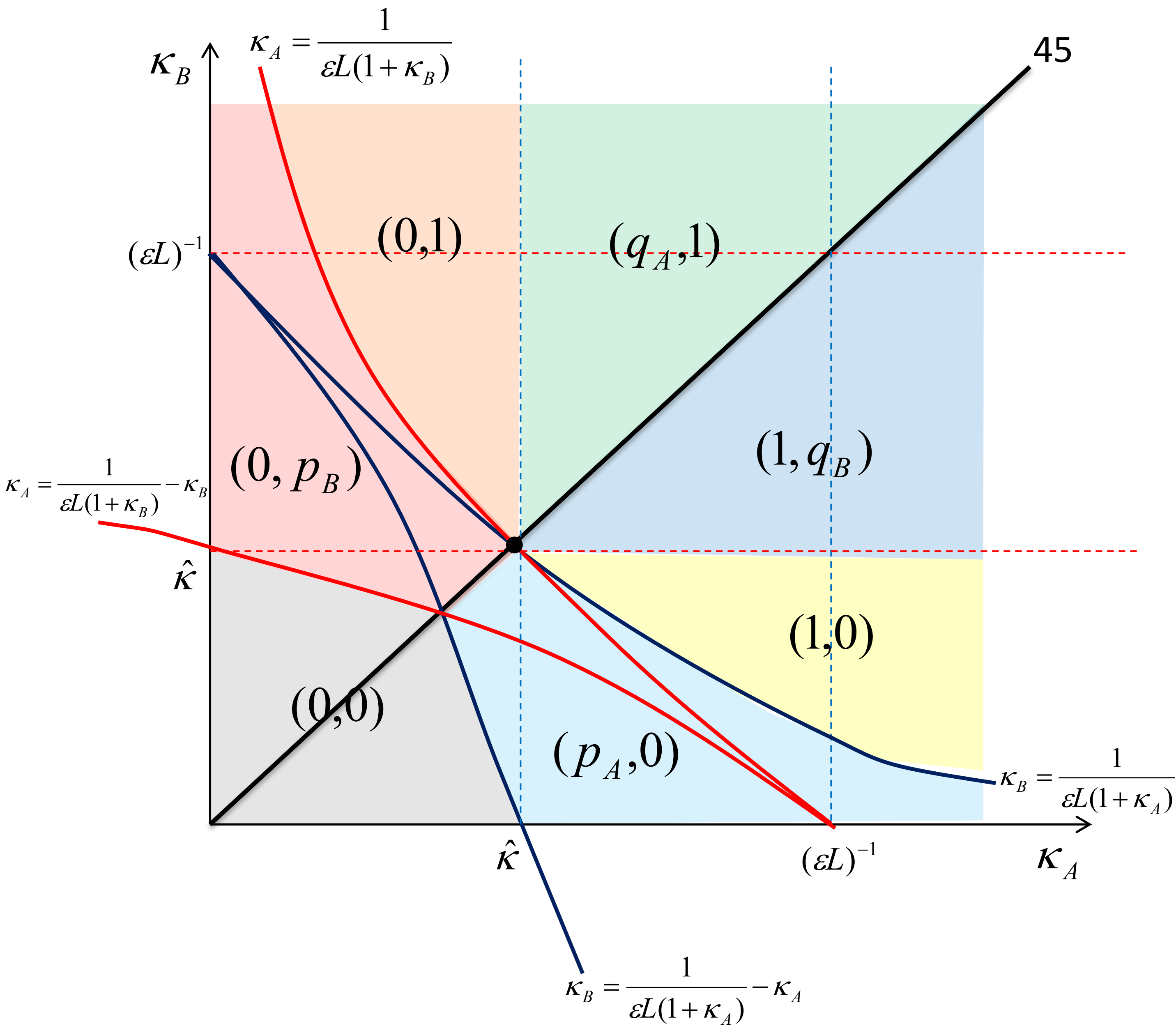

Figure 1: Seven regions of equilibrium policy on a $\kappa_A - \kappa_B$ plane

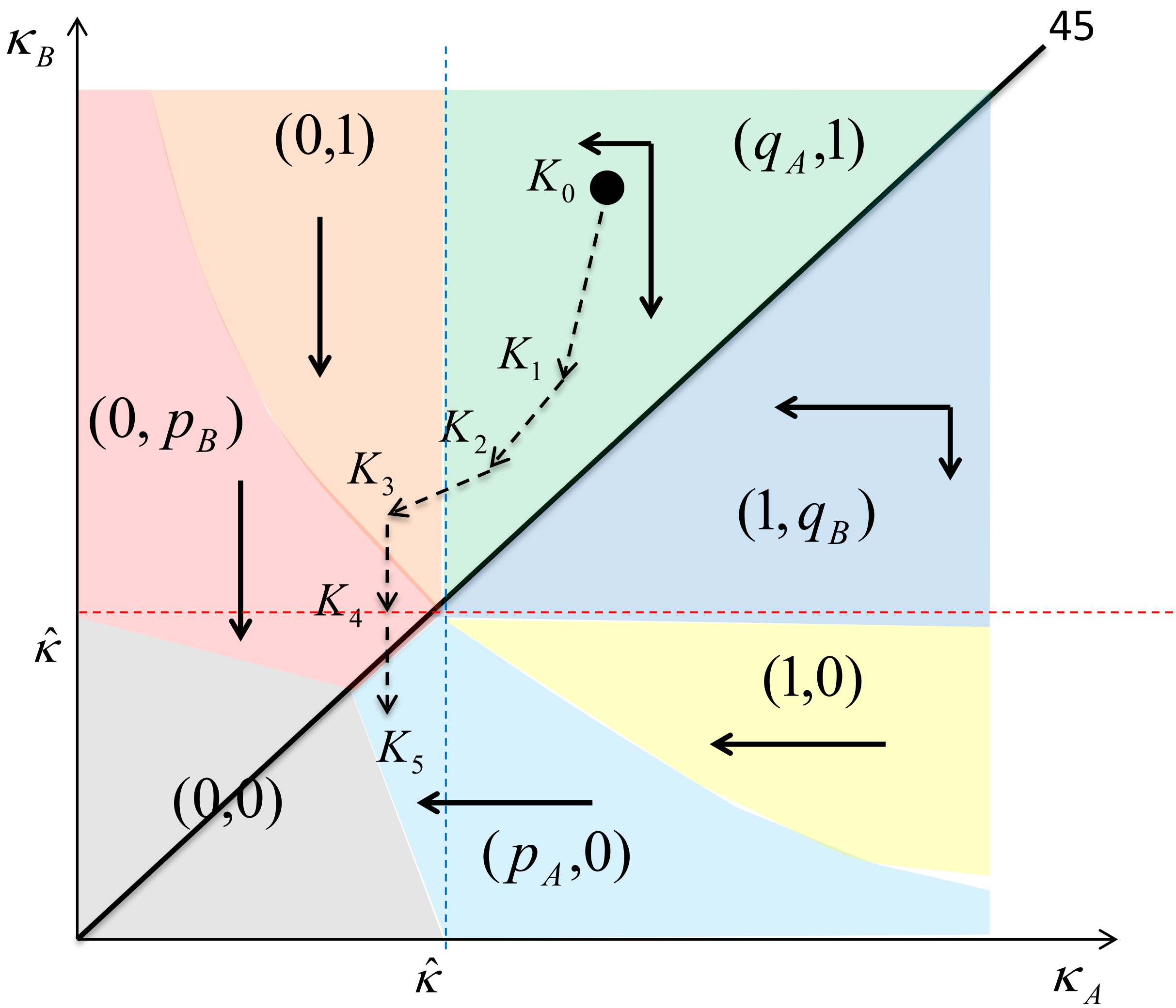

Figure 2: Phase diagram

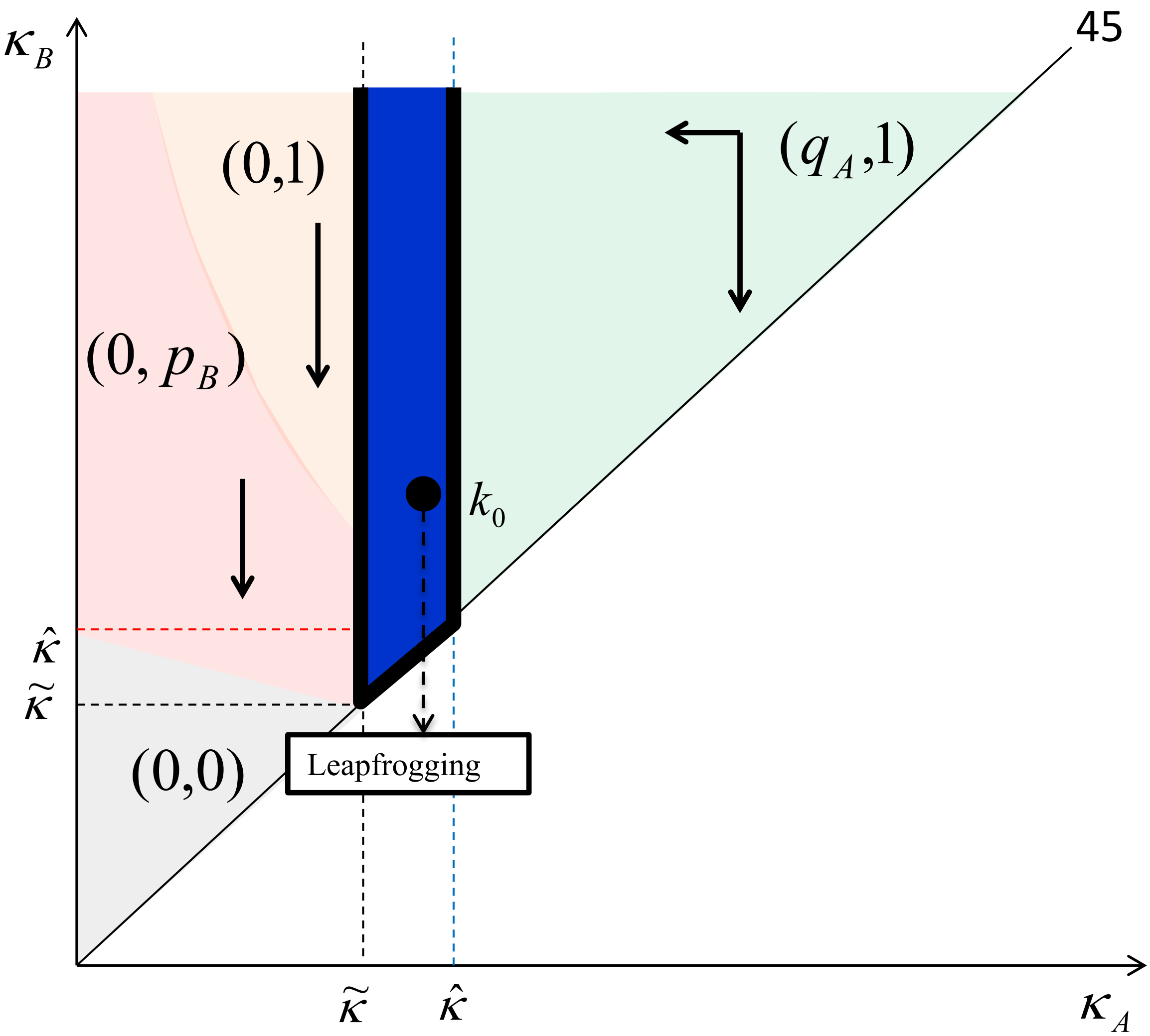

Figure 3 (a): Environmental leapfrogging

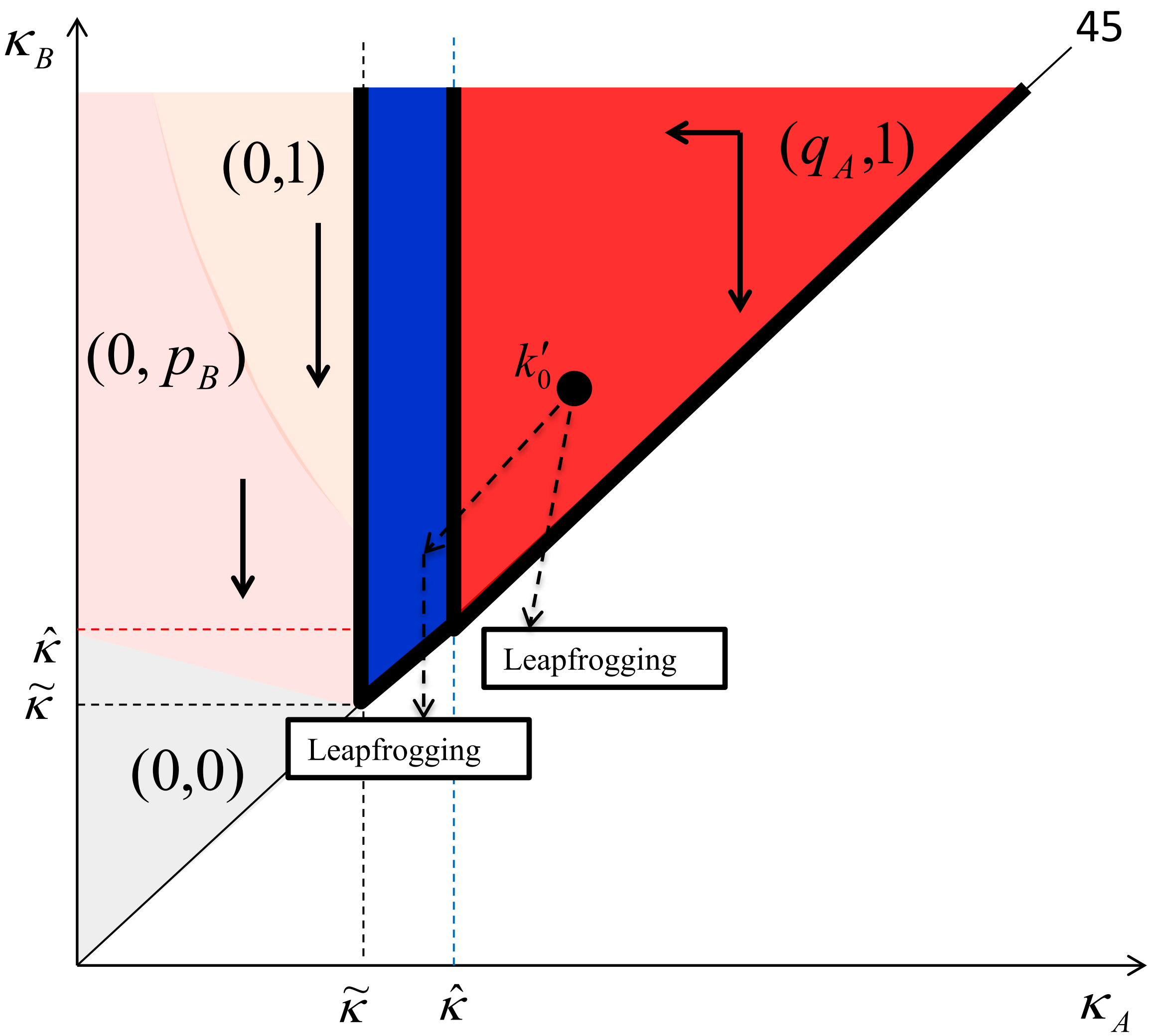

Figure 3(b): Environmental leapfrogging

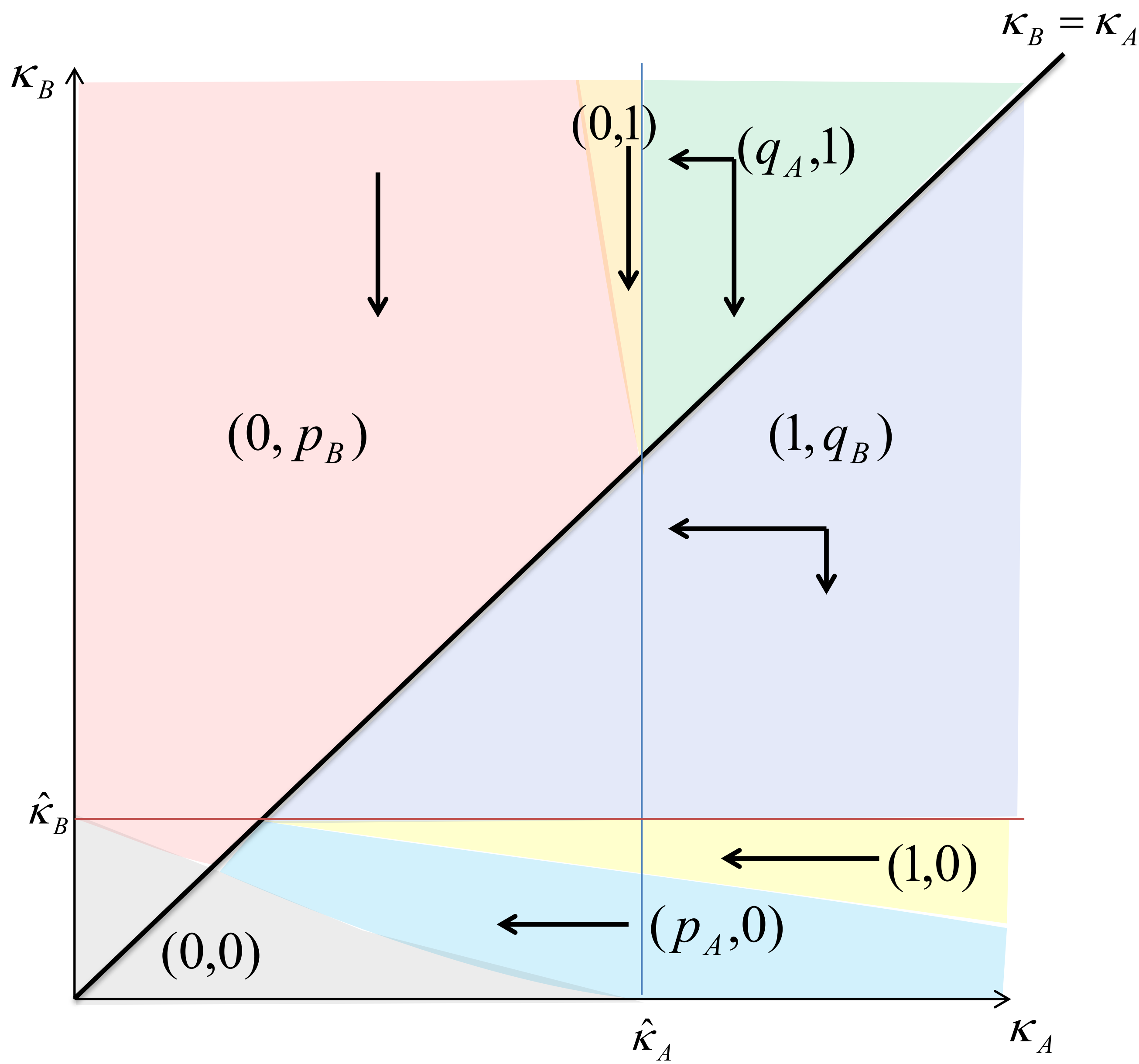

Figure 4 (a): $\varepsilon_A = \varepsilon_B$ and $L_A < L_B$

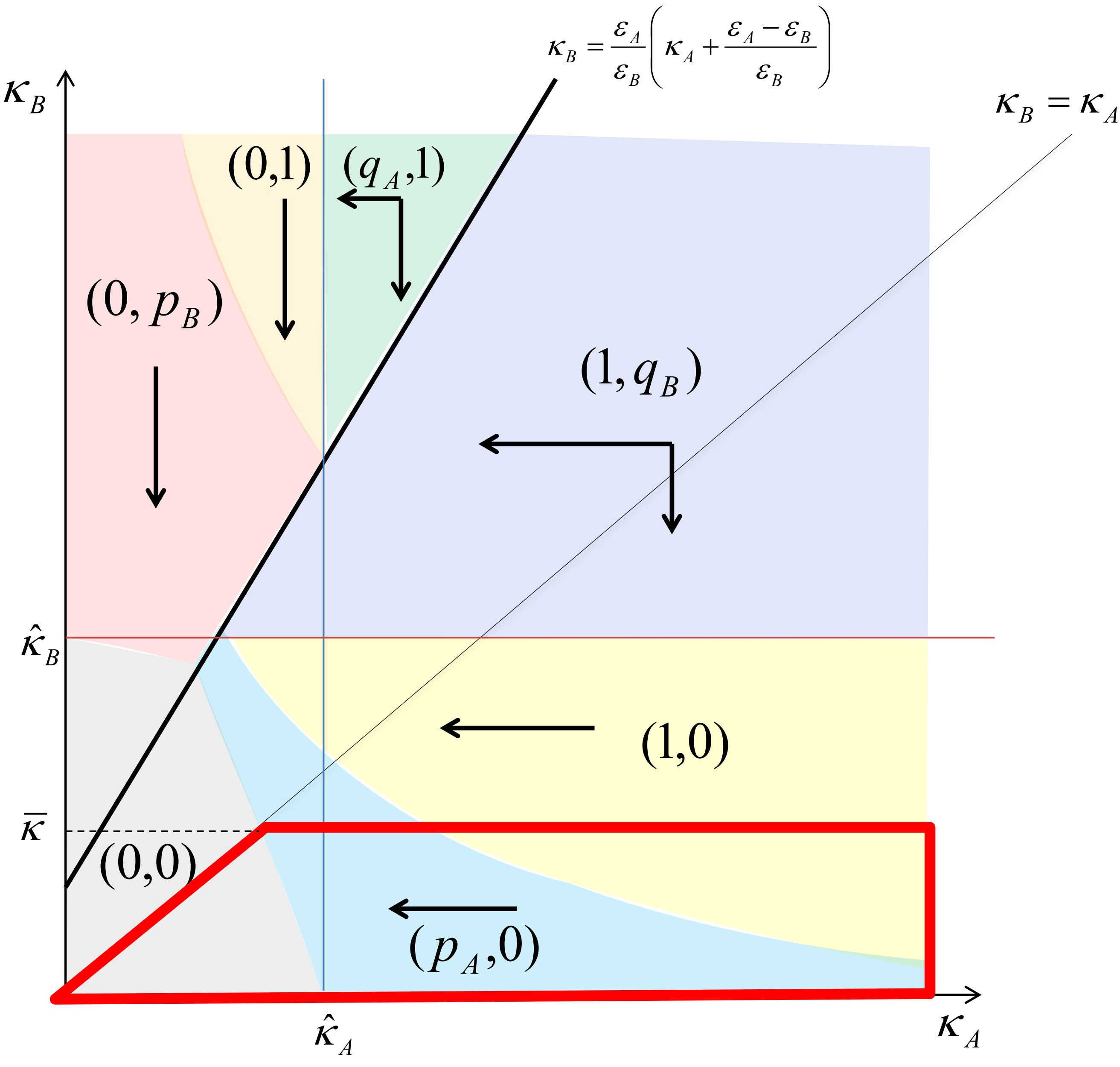

Figure 4 (b): $\varepsilon_A > \varepsilon_B$ and $L_A = L_B$

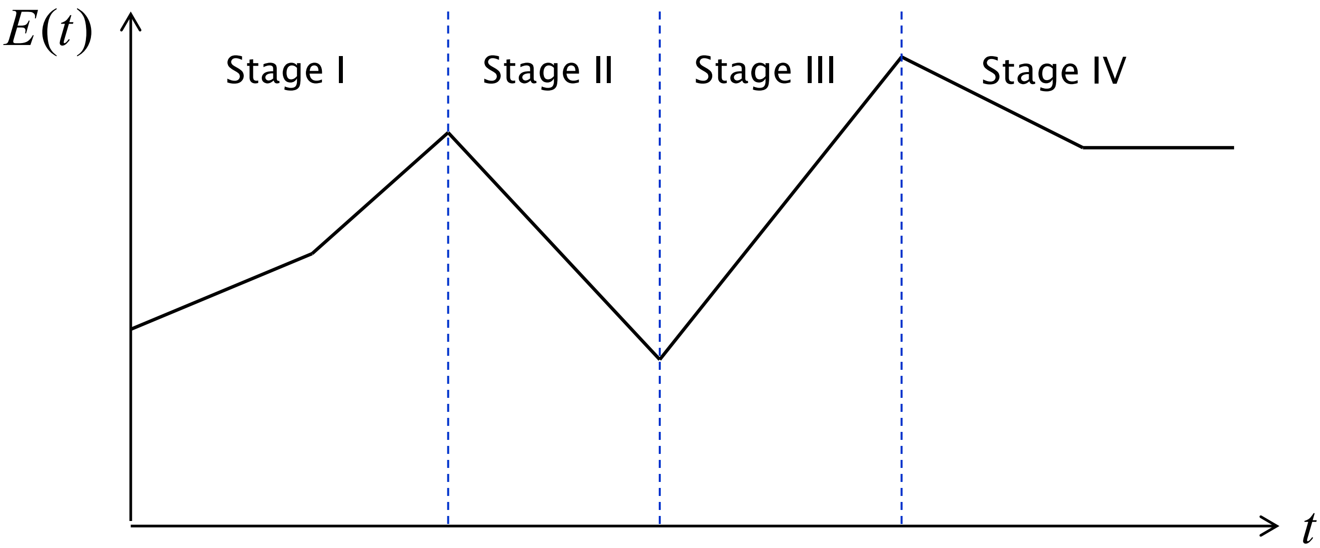

Figure 5 (a): Global pollution without environmental leapfrogging

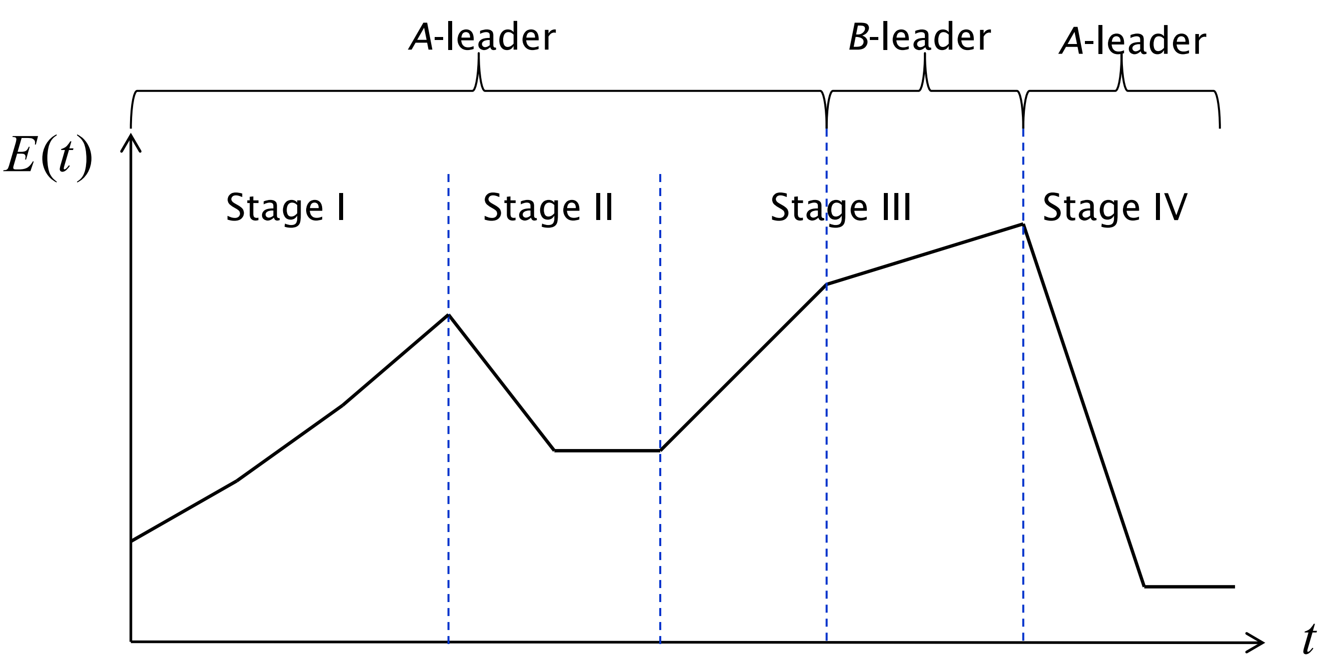

Figure 5 (b): Global pollution with environmental leapfrogging