Environmental Transfers against Global Warming: A Credit-based Program*

Norimichi Matsueda
School of Economics, Kwansei Gakuin University, Uegahara, Nishinomiya, Hyogo 662-8501, Japan

Koichi Futagami
Department of Economics, Osaka University, Machikaneyama, Toyonaka, Osaka 560-0043, Japan

Akihisa Shibata
KIER, Kyoto University, Yoshida, Sakyo-ku, Kyoto 606-8501, Japan

June 2002

Abstract

This paper investigates the impacts of institutionalizing a credit-based transfer program between developing and developed countries. Such a program is expected to become an essence of the Clean Development Mechanism, which is to be implemented shortly. The provisions of financial and technological transfers are incorporated simultaneously into a dynamic game model of global stock pollution where the efficiency in emission abatement is also described as a stock variable. Our numerical simulation indicates that a credit-based transfer program can be more beneficial for a recipient country as well as for a donor country than a non-credit-based transfer program. This is because, with a credit system, the donor country increases the provisions of both economic and technological transfers and the benefits from their increases overwhelm the welfare loss to the recipient country from a reduction in the donor country's abatement efforts.

Key words: global warming, international environmental transfers, Clean Development Mechanism, differential game, open-loop Stackelberg equilibrium

JEL classification: C73, F35, Q20

---

* This paper was originated while the first author was a graduate student at the University of Illinois at Urbana-Champaign. His special thanks go to John Braden for his continuous guidance and Tamer Basar, Dick Brazee and Hayri Onal for their many helpful suggestions. The authors also thank Yasushi Iwamoto, Akiomi Kitagawa, Kazuharu Kiyono, Hideki Konishi, Yasuo Maeda, Fumio Ohtake, Masahiro Okuno-Fujiwara, Katrin Millock, Yoshiyasu Ono, Keijiro Otsuka, Lionel Ragot, Makoto Saito, Aart de Zeeuw and, especially, Ken-ichi Akao for their helpful comments.

1. Introduction

Global warming has become one of the most highlighted international issues of the present day (IPCC (1990) and IPCC (1996)). A main difficulty in dealing with the problem of global warming is that concerned parties are quite dissimilar in their economic positions and political aims. An especially significant dissimilarity lies between developing and developed nations in terms of their historical contributions to global warming as well as the priorities of environmental considerations in their national agendas. The immediate necessity of economic growth in developing nations tends to overshadow environmental concerns although some of them are likely to suffer substantial damages from global warming. Throughout the international negotiations following the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, many developing nations have been extremely reluctant to share the abatement efforts of greenhouse gases with developed nations. On the other hand, in developed countries, domestic concerns about environmental degradation and, possibly, a sense of moral obligation to the international society and future generations could lead to stringent self-controls on their greenhouse-gas emissions. In fact, at the third Conference of the Parties to the UNFCCC (usually referred to as the COP) in 1997, developed nations agreed to reduce the emissions of greenhouse gases, as a whole, to 5.2% below the 1990 level by 2008-2012. A growing anxiety among developed nations is that the increased emissions from developing nations, which are not assigned any emission limits at this moment, could overwhelm their domestic pollutant abatement.[1]

As one of the most promising international actions to combat global warming, the establishment of financial and technological transfer programs has been proposed by both developing and

[1]The potential problem of unilateral actions in the context of global pollution is well-illustrated in Hoel (1991).

developed nations. The need for these transfers was generally accepted at the UNFCCC. Throughout the subsequent COPs, the institutionalization of several specific international transfer mechanisms has been discussed. Most notably, at the third COP in 1997, the implementations of the transfer mechanisms called the Clean Development Mechanism (CDM) and Joint Implementation (JI) were formally included in the so-called Kyoto protocol. These two mechanisms are quite analogous in that they both enable donor nations of financial and technological transfers to receive credits for helping recipient nations conduct further domestic abatement activities -- credits that partially fulfill a donor's domestic abatement responsibility.[2] Therefore, both of these programs will be conducted principally for the purpose of alleviating the burden of developed nations that are obliged to abate greenhouse-gas emissions by certain amounts. With the establishment of these mechanisms, moreover, the global abatement of the pollutant emissions would be conducted more cost-effectively because less expensive abatement options in recipient nations become available as substitutes for more costly abatement activities in donor nations. Furthermore, once these abatement options are available, a greater scale of abatement may be sought globally.

The principal distinction between the CDM and JI is in their donor-recipient relationships. Such a relationship is established between developed and developing nations in the case of the CDM while it is established within developed nations alone for JI.[3] This distinction is important especially because under the Kyoto protocol, only developed nations are obliged to attain certain abatement mandates. Therefore, the former signifies an increase in greenhouse-gas emissions from developed nations due to the use of abatement credits whereas the latter will not lead to an increase in their

---

[2]We refer to this type of credits as "abatement credits" in this study. Formally, they are called "certified emissions reductions (CERs)" for the CDM and "emissions reductions units (ERUs)" in JI.

[3]It might be more appropriate to use the terms, "Annex I parties" and "non-Annex I parties," instead of developed and developing nations, according to the terminology used in the UNFCCC.

emissions as long as the total abatement responsibility assigned to developed nations does not change. In addition, the CDM is expected to contribute to the mitigation of the global warming issue by promoting abatement activities in developing nations that have no binding abatement obligation. Because our interest here is in understanding the consequences of the interaction between developed and developing nations, we focus on the CDM as a credit-based transfer program in this study.

Although the implementation of the CDM is scheduled in the near future, the details and scale of the CDM are still being debated. Certain developing nations are still reluctant to implement such credit-involved transfers to their full extents. They argue, among others, that developed nations would neglect domestic abatement efforts and also that it could result in slower innovations of more efficient abatement technologies by those nations.[4] Meanwhile, yet another form of international cooperation called the Activities Implemented Jointly (AIJ), which does not allow donor countries to earn credits, has been conducted between developing and developed nations in several experimental projects for the purpose of studying the feasibility of prospective CDM and JI projects (Yamin (2000)). In this study, the case with the AIJ is examined mainly for the purpose of distinguishing the effects of a credit system that appears in the CDM, but not in the AIJ. Since a donor country must strictly abide by the predetermined abatement mandate irrespective of the existences of transfers, the motivation for the country to provide transfers in the AIJ defined in this study lies solely in alleviating global warming through the emission reduction by recipient nations,

[4]See Karp and Liu (2000) for the discussions of these arguments. This study does not address such issues as the possibility that the introduction of environmental transfers crowds out more conventional aids that promote economic growth in developing nations. Also, one of the developed nations' concerns about the CDM which are quite relevant to our study is that the CDM might serve as a transitional scheme by developed nations for inducing developing nations to bear the abatement responsibilities in the future since the CDM requires the determinations of the "baseline" abatement levels for developing countries. Here, we purposely ignore this controversy by supposing that, as an international institution, the CDM has acquired long-term commitments by the developed countries.

and not in the saving of its domestic abatement expense as in the case of the CDM.

The objective of this study is to gain insight into the effectiveness and policy implications of these environmental transfer programs, especially, a credit-based program represented by the CDM. Specifically, we compare three plausible scenarios: a case with no transfers, a case with an AIJ-type transfer program which does not allow the acquisition of abatement credits, and a case with a CDM-type transfer program which entails the use of abatement credits. In all three cases an abatement quota is presupposed for a developed nation as an institutional constraint.

The organization of this paper is as follows. In the next section, we consider a situation without the possibility of a transfer program and derive the abatement quota of the developed country as well as the "baseline" abatement level of the developing country. In section 3, we set up a non-cooperative game where a country can provide environmental transfers and, moreover, receive credits for their abatement contributions as in the case of the CDM. We solve this game for its open-loop Stackelberg equilibrium solution. Then, in section 4, we conduct a numerical simulation and make comparisons between the outcomes obtained in the preceding sections in order to understand the effectiveness of each transfer program. The final section summarizes the insight that is obtained from the simulation analysis and describes possible extensions.

2. Situation without Environmental Transfers

Because global warming is essentially a stock pollution problem between multiple decision-makers (Cesar (1994)),[5] our model is constructed as a non-cooperative differential game.[6] In stock

[5]The decision-makers in our model are the governments of concerned nations. For the sake of simplicity, we assume that each government can take effective regulatory policies in controlling the behavior of actual emission sources within its jurisdiction.

pollution, emissions accumulate within an environmental body over time and the scale of the associated damages is directly related to the stock level of the pollutant.[7] A dynamic game can accommodate not only this pollutant accumulation process, but also other stock variables, such as durable goods and technologies used in pollution abatement activities, in the analysis of strategic interactions. Furthermore, the intertemporal feature of a dynamic game enables each player to take into account not only the current decisions of the other players but also their plausible future decisions.

For simplicity, we do not deal with multiple greenhouse gases in this study.[8] This simplification seems rather harmless under the circumstances of global warming because a single gas, CO_2, accounts for 50-80% of the problem (Houghton, Callander and Varney (1992)). While it may fail to capture nuances that could arise if different nations specialize in different gases, the simplification of a single pollutant will enable us to focus on the central question of environmental transfers.[9]

Let us describe the basic structure of our model. Consider a situation with one developing country (country *S*) and one developed country (country *N*). For simplicity, we also suppose that all the different CO_2 abatement options, ranging from the improvement of energy efficiency at emission sources to the sequestration of CO_2 in the atmosphere through afforestation, can be incorporated into a single abatement cost function for each country.

---

[6] See Dockner, Jorgensen, van Long and Sorger (2000), Basar and Olsder (1995), and Mehlmann (1988) for comprehensive accounts of differential games.

[7] On the contrary, the scale of damages in flow pollution is determined by the amount of current emissions alone. For a theoretical analysis on cooperation over transboundary flow pollution, see Braden and Bromley (1981).

[8] Each greenhouse gas has distinct characteristics in terms of its main sources, atmospheric lifetime and contribution to global warming, among others. Hence, differentiated treatment of each gas would be ideal but greatly complicate an analysis.

[9] On the other hand, we should be aware that this simplification might result in significant inefficiencies when other greenhouse gases are much easier to abate, compared to CO_2 (Michaelis (1999)).

Throughout the COPs, developing nations have argued that developed nations are single-handedly responsible for the current global warming problem due to their heavy historical emissions of greenhouse gases. Developed nations finally agreed to impose stringent unilateral abatement mandates on themselves at the third COP. We suppose in this study that the developed country has agreed to select its abatement level that accounts for a certain portion, σ, of the environmental damage cost in the developing country as well as the impacts on itself. Such an abatement level will be imposed upon the developed country as its abatement quota.[10]

Algebraically, the developed country's abatement quota at time t is specified as $a_N(t)$ that minimizes[11]

$$J_N(x(t), a_N(t), t) = \int_0^\infty e^{-r_N t}[d_N(t)(x(t) - x(0)) + \sigma d_S(t)(x(t) - x(0)) + \frac{1}{2}\beta_N(t)a_N(t)^2]dt. \quad (1)$$

In our model, $x(t)$, r_i, $d_i(t)$ and $\beta_i(t)$ respectively represent the atmospheric CO_2 stock level at time t, the instantaneous social discount rate, the marginal cost of the CO_2 stock at time t,[12] and the abatement efficiency parameter of each country i at time t ($i = N$ or S). As an important simplifying assumption, we suppose a linear damage cost function with respect to the accumulation of the CO_2 stock.[13] More specifically, the damage cost is proportional to the difference between the CO_2 stock

[10]The parameter $\sigma (0 \leq \sigma \leq 1)$ would realistically be determined through negotiations between the two countries, but it is supposed to be given exogenously in this study. This assumption enables us to extrapolate a likely future path of the developed country's abatement quota beyond the Kyoto protocol. The choice of an abatement quota will not significantly affect the following analytical outcomes as long as its level is sufficiently greater in relation to the non-cooperative abatement level with no transfer, which will be derived below.

[11]Throughout this study, we do not consider the potential economic benefits arising from CO_2 abatement activities other than the reduction of damages from global warming. The benefits could include the saving on energy usage due to the efficiency improvement of production processes, the alleviations of local environmental issues such as acid rain, and the profits from selling off the byproducts of afforestation.

[12]As usual, the environmental damage cost from global warming is estimated as the monetary value of losses suffered by a typical victim, aggregated over all potential victims.

[13]For simplicity, we assume that the magnitude of the damages is determined by the size of the CO_2 stock in the atmosphere, instead of the increase in the average temperature (e.g. Nordhaus (1994)), whose fluctuation is generally believed to lag behind that of the CO_2 stock level. Also, it has been suspected that greenhouse-gas accumulation may

at time t and the CO_2 stock at a base year, which is assumed here to be the initial year of a time horizon.[14] We also suppose a quadratic abatement cost function with respect to the abatement level, $a_i(t)$, for each country. Note that the integrand in (1) above consists of not only the developed country's own abatement and damage costs but also a certain portion of the damage cost in the developing country. This formulation entails that the developed country must select $a_N(t)$ as if it were experiencing the environmental damages of the developing country to a certain extent as well as its own.

On the other hand, the abatement obligations of developing nations have not even been discussed in the COPs due to their strong oppositions. Reflecting such circumstances, our framework permits a developing country to choose its abatement level freely. In the absence of a transfer, the developing country minimizes the following objective function with respect to $a_S(t)$,

$$J_S(x(t), a_S(t), t) = \int_0^{\infty} e^{-r_S t}[d_S(t)(x(t) - x(0)) + \frac{1}{2}\beta_S(t)a_S(t)^2]dt. \tag{2}$$

Hence, the developing country only considers its own damage and abatement costs, in contrast to the developed country.

Next, we assume that the equation of motion for the CO_2 stock is described as

$$\frac{dx(t)}{dt} = w(e(t) - a_N(t) - a_S(t)) - \rho x(t) \tag{3}$$

where w, $e(t)$ and ρ respectively represent the proportion of the CO_2 emissions that will reach the atmosphere, the amount of the uncontrolled global emissions of CO_2 at time t, and the rate of natural

---

cause catastrophic environmental damages once it surpasses a certain threshold (Gjerde, Grepperud and Kverndokk (1999)). In order to capture this possibility, a non-linear damage cost function would be required. However, a linear specification of a damage cost function is used here for analytical ease as an approximation within a certain range of the CO_2 stock.

[14]Since a damage cost function is assumed to be linear, the choice of this base year does not matter significantly in our analysis unless the stock level at time t becomes smaller than its initial size, which is predicted very unlikely, at least,

assimilation of the pollutant stock. The existence of the coefficient w reflects the fact that a certain portion of CO_2 emissions is captured by natural sinks, such as the oceans, before reaching the atmosphere. The parameter ρ is related to the atmospheric lifetime of CO_2, and the last term in (3) specifies that natural assimilation of the pollutant stock occurs linearly with respect to its current level. In other words, the pollutant assimilation process is described here as a "constant exponential rate of decay," which is not a bad description for the assimilation of greenhouse gases (Michaelis (1994)).

The efficiency of CO_2 abatement activities in each country at time t is represented by $\beta_i(t)$ ($i = S$, or, N). A smaller $\beta_i(t)$ signifies that the country is more efficient in abatement activities. We suppose that, in the absence of a technological transfer, the abatement efficiency of the developing country always lags behind that of the developed country by a certain margin. Denoting this lag by a constant z ($z > 0$), we express $\beta_S(t)$ as

$$\beta_S(t) = \beta_N(t) + z. \tag{4}$$

Here, the abatement efficiency parameter of the developed country, $\beta_N(t)$, is given exogenously. This formulation implies that, as $\beta_N(t)$ falls over time, the technological gap between developed and developing countries widens in percentage terms although the absolute value of $\beta_S(t)$ decreases concurrently.

From the four equations above, we can set up the current-value Hamiltonian of the developing country as

$$H_S(x(t), a_N(t), a_S(t), \lambda_S(t), t) = d_S(t)(x(t) - x(0)) + \frac{1}{2}(\beta_N(t) + z)a_S(t)^2$$
$$+ \lambda_S(t)\{w(e(t) - a_N(t) - a_S(t)) - \rho x(t)\}. \tag{5}$$

---

within the next century or so (IPCC (1990)).

In this Hamiltonian equation, $\lambda_S(t)$ is the developing country's co-state variable assigned for $x(t)$. As a necessary condition for minimization, $\lambda_S(t)$ needs to satisfy[15]

$$\frac{d\lambda_S(t)}{dt} = r_S\lambda_S(t) - \frac{\partial H_S}{\partial x(t)} = (r_S + \rho)\lambda_S(t) - d_S(t). \tag{6}$$

Since this is a simple linear first-order ordinary differential equation, the explicit solution to (6) can easily be derived by imposing the transversality condition, $\lim_{t\to\infty} e^{-r_S t}\lambda_S(t) = 0$. After some manipulations, it can be shown that

$$\lambda_S(t) = \int_t^\infty d_S(v)e^{-(r_S+\rho)(v-t)}dv \tag{7}$$

As an additional assumption, we consider that the magnitude of the marginal environmental damage cost in country *i* changes over time at a constant rate θ_i.[16] That is

$$d_i(t) = d_i(0)e^{\theta_i t}. \tag{8}$$

Furthermore, in accordance with the previous studies in this area such as Nordhaus (1991), we suppose $\theta_i < r_i + \rho$. This implies that the growth rate of the marginal damage cost cannot exceed the sum of its social discount rate and the rate of pollutant assimilation. Under these assumptions, equation (6) can be reduced to

$$\lambda_S(t) = \frac{d_S(t)}{r_S + \rho - \theta_S}. \tag{9}$$

Hence, the value of $\lambda_S(t)$ is determined solely by exogenous parameters alone with the formulations above.

---

[15]With the given functional forms, the following necessary conditions are also sufficient for the minimization of the Hamiltonian. This remark also applies to the other necessary conditions in this study. See Arrow and Kurz (1970) for sufficiency conditions of optimal control problems.

[16]At least, θ_i would be dependent on the following three factors (Falk and Mendelsohn (1993)). Population growth could force the damages per ton of the CO_2 stock to increase over time, and the growth in GDP per capita is also likely to raise the damage cost since willingness to pay for environmental improvement tends to increase with income. On the other hand, improvement in adaptation could reduce the damages over time. The value of θ_i would be determined as a

Also, the minimization condition of the developing country, $\partial H_S/\partial a_S(t) = 0$, yields

$$(\beta_N(t)+z)a_S(t)-\lambda_S(t)w=0 \Rightarrow a_S(t)=\frac{\lambda_S(t)w}{\beta_N(t)+z}. \tag{10}$$

Then, combining (9) with (10), we have the non-cooperative abatement level of the developing country at time t, $a_S^N(t)$, as

$$a_S{}^N(t)=\frac{d_S(t)w}{(r_S+\rho-\theta_S)(\beta_N(t)+z)}. \tag{11}$$

The absence from (11) of the control and state variables that can be influenced by the developed country implies that the developing country's abatement level turns out to be determined independently of the other country's strategy in a situation with no transfer program. In particular, the choice of an abatement level by the developed country does not affect the determination of $a_S^N(t)$ by the developing country. This is mainly due to the linear specifications of its damage cost function and the assimilation function for the CO_2 stock.

In order to obtain the abatement quota of the developed country at time t, $a_N^Q(t)$, we set up the Hamiltonian for this country as

$$H_N(x(t),a_N(t),a_S(t),\lambda_N(t),t)=d_N(t)(x(t)-x(0))+\sigma d_S(t)(x(t)-x(0))+\frac{1}{2}\beta_N(t)a_N(t)^2$$
$$+\lambda_N(t)\{w(e(t)-a_N(t)-a_S(t))-\rho x(t)\}. \tag{12}$$

As a necessary condition for minimization, $\lambda_N(t)$ must satisfy

$$\frac{d\lambda_N(t)}{dt}=r_N\lambda_N(t)-\frac{\partial H_N}{\partial x(t)}=(r_N+\rho)\lambda_N(t)-(d_N(t)+\sigma d_S(t)). \tag{13}$$

In the same fashion as in the derivation of $\lambda_S(t)$ above, the developed country's co-state variable on $x(t)$ can be obtained as

---

combination of these factors among others.

$$\lambda_N(t) = \frac{d_N(t)}{r_N + \rho - \theta_N} + \frac{\sigma d_S(t)}{r_N + \rho - \theta_S}. \tag{14}$$

Also, the minimization condition of the developing country, $\partial H_N/\partial a_N(t) = 0$, yields

$$\beta_N(t)a_N(t) - \lambda_N(t)w = 0 \Rightarrow a_N(t) = \frac{\lambda_N(t)w}{\beta_N(t)}. \tag{15}$$

Combining (14) with (15), we have the abatement quota of the developed country at time t, $a_N^Q(t)$, as

$$a_N^Q(t) = (\frac{d_N(t)}{r_N + \rho - \theta_N} + \frac{\sigma d_S(t)}{r_N + \rho - \theta_S})\frac{w}{\beta_N(t)}. \tag{16}$$

Without the obligation of taking the developing country's damage cost into account (i.e., $\sigma = 0$), the developed country would choose its non-cooperative abatement level with no transfer, $a_N^N(t)$, as

$$a_N^N(t) = \frac{d_N(t)w}{(r_N + \rho - \theta_N)\beta_N(t)}. \tag{17}$$

As expected, the abatement quota determined by (16) is greater than the non-cooperative abatement level of (17) due to the inclusion of the second term in the parenthesis of (16). The non-cooperative solution to a game without transfers and the abatement quota would consist of $a_N^N(t)$ and $a_S^N(t)$. Moreover, this combination defines its feedback as well as open-loop Nash equilibrium solution due to the fact that this game is so-called "perfect game" (Fershtman (1987) and Mehlmann (1988)). Unlike this case, the analytical derivation of a feedback equilibrium of the environmental transfer game in the next section would be extremely difficult due to some additional complications, such as multiple state variables. Hence, we will conduct our analysis solely within an open-loop information framework. We could justify this information structure, for instance, by supposing serious loss of reputation that a country would incur by deviating from its previously-announced strategy. An open-loop approach is frequently used in the economics literature when a feedback equilibrium is impossible to obtain (e.g. Petit (1989) and van Aarle, Bovenberg and Raith (1995)).[17]

3. Environmental Transfers

In this section, we formulate a situation where the developed country can provide two types of environmental transfers and, moreover, obtain abatement credits from these provisions in the case of the CDM. We suppose that, due to an international treaty, the abatement quota of the developed country is fixed at $a_N^Q(t)$ obtained in the previous section throughout the horizon.[18] However, the country can now use two types of transfers: *economic* and *technological* transfers. An economic transfer is a monetary instrument that one country can provide for the purpose of encouraging the other country to undertake further abatement efforts. We suppose that the economic transfer will be supplied from the developed country to the developing country in certain proportion to the total abatement expense of the developing country. The proportion might be called the "economic transfer ratio" and denoted by $\gamma(t)$ $(0 \leq \gamma(t) < 1)$.[19]

A technological transfer is an investment in physical devices or in R & D activities specifically targeted for CO_2 abatement activities within the developing country. Especially, we assume that the abatement efficiency of the developing country can be intentionally augmented through a technological transfer by the developed country, which is supposed to possess superior technologies and knowledge regarding the abatement activities. Moreover, it seems reasonable to consider that

[17]For the comparisons of the outcomes arising from the different information structures of players, see van der Ploeg and de Zeeuw (1992) and Maler and de Zeeuw (1998) in the context of international environmental problems.

[18]The baseline level may be determined endogenously, depending on the transfer mechanisms and the rate at which the developed country receives credits in returns for its transfers. However, for simplicity, we employ this assumption.

[19]The case $\gamma(t) = 1$ is excluded because this would lead the developing country to choose an infinite amount of abatement.

the abatement efficiency is a stock variable because a wide range of durable devices, management skills and knowledge, which usually accumulate over time, can be considered to be significant determinants of abatement efficiency.

We now examine the open-loop Stackelberg equilibrium of this environmental transfer game. We suppose that the developed country plays the role of a Stackelberg leader as a donor of transfers and the developing country assumes the role of a Stackelberg follower as a recipient. More specifically, the developed country first announces the time paths of the economic transfer ratio and the level of the technological transfer. Then, the developing country chooses the level of its domestic abatement, treating the developed country's announcements as given.

A credibility issue usually arises in an open-loop Stackelberg equilibrium solution: a leader's strategy would become time-inconsistent (de Zeeuw and van der Ploeg (1991)).[20] Fortunately, however, it will turn out that the strategy of the leader in the open-loop Stackelberg equilibrium of the following game is time-consistent, due to our particular choices of functional forms.

In the case of the CDM, the developed country can obtain abatement credits that are substitutable for its domestic abatement responsibilities. We suppose that the credits are granted for helping the other country make additional abatement efforts in excess of its non-cooperative level with no transfer, $a_S^N(t)$, which was derived in the previous section.[21] Therefore, the non-cooperative abatement level of the developing country with no transfer is considered a "baseline" abatement level for this country.[22] Moreover, we introduce a predetermined constant l ($0 \leq l < 1$) that signifies

---

[20] Time-inconsistency would not occur in a feedback Stackelberg equilibrium solution, which is not only time-consistent but also subgame-perfect by construction. However, the latter solution is often difficult to obtain and, in the model developed here, an analytical solution is not possible.

[21] The system of the CDM assumed here is based on the idea of "additionality". See Yamin (2000) for its discussion.

[22] This assumption is made for analytical simplicity. It is still quite controversial how this baseline abatement level should be determined for a CDM project.

the ratio by which an extra abatement of the developing country in excess of this baseline abatement level is converted into the amount of abatement credits that the developed country will receive.[23] In particular, an AIJ-type transfer program can be represented by the case where the value of l is equal to zero. In such a case, the developed country cannot obtain any abatement credit.

Algebraically, the amount of the abatement credits that the developed country can receive becomes

$$c(t) = l(a_S(t) - a_S{}^N(t)) \tag{18}$$

if $c(t) > 0$ and otherwise, $c(t)$ is equal to zero. Supposing the full use of the credits by the developed country,[24] the equation of motion for the CO_2 stock is rewritten as

$$\frac{dx(t)}{dt} = w\{e(t) - (a_N{}^Q(t) - c(t)) - a_S(t)\} - \rho x(t). \tag{19}$$

The actual abatement of the developed country is now expressed as $a_N^Q(t) - c(t)$, which will be denoted by $a_N^C(t)$ in the following simulation. Hence, the amount of the abatement credits that the developed country has obtained can partially substitute for its abatement responsibility. Furthermore, equation (18) could be substituted into this equation of motion.

The developed country controls the economic transfer ratio, $\gamma(t)$, and the level of the technological transfer, $T(t)$, to minimize

$$J_N(x(t), \gamma(t), a_S(t), T(t), t) = \int_0^\infty e^{-r_N t}[d_N(t)(x(t) - x(0)) + \frac{1}{2}\beta_N(t)(a_N{}^Q(t) - c(t))^2$$

---

[23]We exclude the case where the value of l is equal to 1. For such a value of l, the acquired abatement credits allow the developed country to reduce the domestic abatement level by the same amount as the developing country has increased its abatement level due to the transfer programs. In our particular setting, such a mechanism will eradicate the incentive of the developing country to make any additional abatement efforts in anticipation of the reaction by the developed country.

[24]This implies either that the value of l is kept small enough to make the actual abatement of the developed country, i.e., $a_N^Q(t) - c(t)$, greater than its non-cooperative abatement level, $a_N^N(t)$, which is given by (17), or that the difference between $a_N^Q(t)$ and $a_N^N(t)$ is sufficiently large. Otherwise, there will be superfluous abatement credits.

$$+\frac{1}{2}\gamma(t)\beta_S(t)a_S(t)^2+T(t)]dt. \tag{20}$$

The third term and the fourth term within the integrand of (20) respectively correspond with the amounts of economic and technological transfers.

On the other hand, the objective of the developing country is to minimize the following function with respect to $a_S(t)$,

$$J_S(x(t),\gamma(t),a_S(t),t)=\int_0^\infty e^{-r_S t}[d_S(t)(x(t)-x(0))+\frac{1}{2}(1-\gamma(t))\beta_S(t)a_S(t)^2]dt. \tag{21}$$

Due to the economic transfer, the abatement cost of the developing country is reduced by the proportion of $1\text{-}\gamma(t)$ from its abatement cost in the case without the transfer.

Additionally, because of the technological transfer, the abatement efficiency of the developing country could improve more rapidly than without the transfer. We express such an improvement as a decrease in $\beta_S(t)$ of its abatement cost function. Similarly to equation (4), we assume

$$\beta_S(z(t),t)=\beta_N(t)+z(t). \tag{22}$$

In equation (22), $z(t)$ is a non-negative stock variable, which can be affected by the technological transfer from the developed country as

$$\frac{dz(t)}{dt}=-\alpha T(t)^\delta \tag{23}$$

where α and δ are non-negative time-invariant parameters.

Given the formulation of this environmental transfer game, we can write the Hamiltonian of the developing country as

$$H_S(x(t),\gamma(t),z(t),a_S(t),\mu_S(t),\lambda_S(t),t)=d_S(t)(x(t)-x(0))+\frac{1}{2}(1-\gamma(t))(\beta_N(t)+z(t))a_S(t)^2$$
$$-\mu_S(t)\alpha T(t)^\delta+\lambda_S(t)[w\{e(t)-a_N{}^Q(t)-la_S{}^N(t)-(1-l)a_S(t)\}-\rho x(t)], \tag{24}$$

where $\mu_S(t)$ and $\lambda_S(t)$ are the developing country's co-state variables for $z(t)$ and $x(t)$, respectively.

As a necessary condition for minimization, $\lambda_S(t)$ needs to satisfy

$$\frac{d\lambda_S(t)}{dt} = r_S\lambda_S(t) - \frac{\partial H_S}{\partial x(t)} = (r_S + \rho)\lambda_S(t) - d_S(t). \tag{25}$$

Just as in the previous section, equation (25) can be reduced to

$$\lambda_S(t) = \frac{d_S(t)}{r_S + \rho - \theta_S}. \tag{26}$$

Also, the minimization condition, $\partial H_S/\partial a_S(t) = 0$, determines $a_S(t)$ as

$$(1-\gamma(t))(\beta_N(t) + z(t))a_S(t) - \lambda_S(t)w(1-l) = 0 \Rightarrow a_S(t) = \frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))}. \tag{27}$$

This is the optimal abatement strategy of the developing country, given the values of $\gamma(t)$ and $z(t)$.[25]

In this Stackelberg game, the developing country observes the values of $\gamma(t)$ and $T(t)$ chosen by the developed country at each instant before it decides upon the level of $a_S(t)$. Hence, equation (27) is the developing country's reaction function toward the choices of $\gamma(t)$ and $T(t)$, which contributes to lowering $z(t)$, by the developed country. As can be easily expected, an increase in $\gamma(t)$ will induce the developing country to raise $a_S(t)$. From equation (27), we can also observe that $a_S(t)$ is negatively related to the level of $\beta_S(t)$ (= $\beta_N(t) + z(t)$). Hence, each provision of the economic transfer and of the technological transfer leads to greater abatement by the developing country. Here, these transfers by the developed country and the abatement efforts made by the developing country are characterized as "strategic complements". On the other hand, the addition of the credit system appears to decrease the abatement level of the developing country due to the existence of the term (1-l) in the numerator of (27). However, the overall influence of the credit mechanism upon $a_S(t)$ is ambiguous because its implementation also affects the time-paths of the two types of transfers, as

[25] Unlike the previous section, we do not insert equation (26) into $\lambda_S(t)$ in (27) for the simplicity of following expositions, which does not lead to any loss of generality because $\lambda_S(t)$ is determined independently of the developed country's action in this problem.

we will observe below.

Incorporating (27) into the current-value Hamiltonian of the developed country (country *N*) yields

$$H_N(x(t),\gamma(t),z(t),T(t),\mu_N(t),\lambda_N(t),t) = d_N(t)(x(t)-x(0))$$
$$+\frac{1}{2}\beta_N(t)[a_N{}^Q(t)-l\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))}\}+la_S{}^N(t)]^2$$
$$+\frac{1}{2}\gamma(t)(\beta_N(t)+z(t))\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))}\}^2+T(t)-\mu_N(t)\alpha T(t)^\delta$$
$$+\lambda_N(t)[w\{e(t)-a_N{}^Q(t)-la_S{}^N(t)-(1-l)\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))}\}-\rho x(t)], \quad (28)$$

where $\mu_N(t)$ and $\lambda_N(t)$ are the developed country's co-state variables for $z(t)$ and $x(t)$, respectively. From the Minimum Principle, the time-path of $\lambda_N(t)$ follows the auxiliary equation,

$$\frac{d\lambda_N(t)}{dt} = r_N\lambda_N(t)-\frac{\partial H_N}{\partial x(t)} = (r_N+\rho)\lambda_N(t)-d_N(t). \quad (29)$$

In the same manner as $\lambda_S(t)$ in the previous section, equation (29) could be reduced to

$$\lambda_N(t) = \frac{d_N(t)}{r_N+\rho-\theta_N}. \quad (30)$$

On the other hand, the time-path of $\mu_N(t)$, the co-state variable for $z(t)$, follows the auxiliary equation,

$$\frac{d\mu_N(t)}{dt} = r_N\mu_N(t)-\frac{\partial H_N}{\partial z(t)} = r_N\mu_N(t)-[\beta_N(t)l\{a_N{}^Q(t)$$
$$-\frac{\lambda_S(t)w(1-l)l}{(1-\gamma(t))(\beta_N(t)+z(t))}+la_S{}^N(t)\}\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))^2}\}$$
$$-\frac{\gamma(t)}{2}\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))}\}^2+\lambda_N(t)w\frac{\lambda_S(t)w(1-l)^2}{(1-\gamma(t))(\beta_N(t)+z(t))^2}]. \quad (31)$$

The minimization condition with respect to $T(t)$, $\partial H_N/\partial T(t)=0$, leads to

$$1-\mu_N(t)\alpha\delta T(t)^{\delta-1}=0 \Rightarrow \mu_N(t)=\frac{1}{\alpha\delta}T(t)^{1-\delta}. \tag{32}$$

Taking the time-derivative of (32), we obtain

$$\frac{d\mu_N(t)}{dt}=\frac{1-\delta}{\alpha\delta}T(t)^{-\delta}\frac{dT(t)}{dt}. \tag{33}$$

Substituting (32) and (33) into (31), we have

$$\begin{aligned}\frac{1-\delta}{\alpha\delta}T(t)^{-\delta}\frac{dT(t)}{dt}&=\frac{r_N}{\alpha\delta}T(t)^{1-\delta}-[\beta_N(t)l\{a_N{}^Q(t)\\&-\frac{\lambda_S(t)w(1-l)l}{(1-\gamma(t))(\beta_N(t)+z(t))}+la_S{}^N(t)\}\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))^2}\}\\&-\frac{\gamma(t)}{2}\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))}\}^2+\lambda_N(t)w\frac{\lambda_S(t)w(1-l)^2}{(1-\gamma(t))(\beta_N(t)+z(t))^2}].\end{aligned} \tag{34}$$

Rearranging the terms, we eventually have

$$\begin{aligned}\frac{dT(t)}{dt}&=\frac{r_N}{1-\delta}T(t)-\frac{\alpha\delta}{1-\delta}T(t)^{\delta}[\beta_N(t)l\{a_N{}^Q(t)\\&-\frac{\lambda_S(t)w(1-l)l}{(1-\gamma(t))(\beta_N(t)+z(t))}+la_S{}^N(t)\}\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))^2}\}\\&-\frac{\gamma(t)}{2}\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))}\}^2+\lambda_N(t)w\frac{\lambda_S(t)w(1-l)^2}{(1-\gamma(t))(\beta_N(t)+z(t))^2}].\end{aligned} \tag{35}$$

Equation (35) implicitly describes the optimal time-path of $T(t)$ from the viewpoint of the developed country.

Finally, the minimization condition with respect to $\gamma(t)$, i.e., $\partial H_N/\partial\gamma(t)=0$, yields

$$\begin{aligned}&-[a_N{}^Q(t)-l\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))}\}+la_S{}^N(t)]\beta_N(t)l\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))^2(\beta_N(t)+z(t))}\}\\&+\frac{1}{2}(\beta_N(t)+z(t))\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))}\}^2\\&+\gamma(t)(\beta_N(t)+z(t))\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))}\}\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))^2(\beta_N(t)+z(t))}\}\end{aligned}$$

$$-\lambda_N(t)w(1-l)\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))^2(\beta_N(t)+z(t))}\}=0. \tag{36}$$

This equation can be transformed to

$$\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))}\}^2(\beta_N(t)+z(t))\left[-[a_N{}^Q(t)-l\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))}\}\right.$$
$$\left.+la_S{}^N(t)]\frac{\beta_N(t)l}{\lambda_S(t)w(1-l)}+\frac{1}{2}+\frac{\gamma(t)}{1-\gamma(t)}-\frac{\lambda_N(t)}{\lambda_S(t)}\right]=0. \tag{37}$$

In order for equation (37) to be satisfied, the terms within the last bracket must add up to zero. That is,

$$-[a_N{}^Q(t)-l\{\frac{\lambda_S(t)w(1-l)}{(1-\gamma(t))(\beta_N(t)+z(t))}\}+la_S{}^N(t)]\frac{\beta_N(t)l}{\lambda_S(t)w(1-l)}+\frac{1}{2}+\frac{\gamma(t)}{1-\gamma(t)}-\frac{\lambda_N(t)}{\lambda_S(t)}=0. \tag{38}$$

We can solve this for $\gamma(t)$ and obtain

$$\gamma(t)=\frac{X-Y}{X+1}, \tag{39}$$

where

$$X=\frac{\beta_N(t)l}{\lambda_S(t)w(1-l)}(a_N{}^Q(t)+la_S{}^N(t))-\frac{1}{2}+\frac{\lambda_N(t)}{\lambda_S(t)} \text{ and } Y=\frac{\beta_N(t)l^2}{\beta_N(t)+z(t)}.$$

This is the optimal choice of the economic transfer ratio from the developed country's perspective. The selection of $\gamma(t)$ by the developed country will be substituted for $\gamma(t)$ in equation (27), which yields, together with (26), the equilibrium value of $a_S(t)$ chosen by the developing country.

Combining the results above, the open-loop Stackelberg equilibrium solution of this dynamic game is represented by the system of equations, (18), (19), (22), (23), (26), (27), (30), (35) and (39).[26] Notice that, in our model, only the developed country is able to intentionally affect the value

[26] Additionally, we need the initial level of the technological transfer in order to specify the time paths of the variables in this equilibrium. We will explain how to actually determine the equilibrium value of $T(0)$ in the following simulation section.

of $\beta_S(t)$ throughout the time-horizon. More significantly, $\lambda_S(t)$, which is the developing country's co-state variable on $x(t)$ and given by (26), turns out to be determined independently of the actions taken by the developed country. In other words, $\lambda_S(t)$ is not controllable by the actions of the developed country in the sense that $\lambda_S(t)$ cannot be moved around by the provisions of environmental transfers. It follows that the strategy of the leader in this open-loop Stackelberg equilibrium is indeed time-consistent (see Xie (1997), Mino (2000) and Dockner et al. (2000)). That is, the time-paths of the variables obtained above will also constitute the open-loop equilibrium in any of its truncated game as long as the actions taken in preceding periods are those specified by the equilibrium paths. Therefore, the policy announcement of the developed country becomes credible, even without a binding commitment to its global strategies. This result is mainly due to the linearity assumptions regarding the assimilation and damage cost functions of the two countries.

4. Simulation Analysis

In this section, we conduct a simple numerical simulation of potential strategic cooperation over global warming in order to discuss the dynamic paths of the significant variables and their policy implications. As preparations for the following simulation, we need to make some additional assumptions and specify parameter values.[27] We elect to present the simulation results only for the first hundred years, following the pattern of the scientific studies on global warming (e.g. IPCC (1990)). Given the current and expected emissions of developed and developing nations, the amount of the uncontrolled global CO_2 emissions, $e(t)$, is described as $e(t) = 5.0e^{0.005t} + 3.0e^{0.01t}$

[27]Monetary and physical units used in this simulation are respectively billion U.S. dollars and billion tons of carbon (GtC).

(billion tons of carbon).[28] This value is approximated from the parameters in Tahvonen (1994), who divides the world into five regions: USA, the other OECD countries, the former Soviet Union and Eastern Europe, China, and, the rest of the world. Here, we classify the first three regions as the developed "country" and the next two regions as the developing "country", following the compositions of Annex I and non-Annex I parties in the UNFCCC.

The initial values of marginal damage costs per million carbon tons are estimated as $d_N(0) = 0.4$ and $d_S(0) = 0.2$, which are also based roughly on the parameters in Tahvonen (1994). Additionally, we suppose that the growth rates of the marginal damage costs for the two countries are $\theta_N = 0.005$ and $\theta_S = 0.01$, respectively. The other parameter values are specified as follows: $r_S = 0.03$, $r_N = 0.02$, $w = 0.6$, $\rho = 0.003$, $x(0) = 700$, $\beta_N(t) = 20 - 0.1t$, $z(0)$ $(= z) = 20$, $\delta = 0.5$ and $\alpha = 0.2$. The values of the first six parameters would be considered reasonable in the light of previous simulation studies on global warming, such as Nordhaus (1991), Cline (1991), Nordhaus (1994), Tahvonen (1994) and Farzin (1996). However, the last three parameters are more troublesome since we do not have even rough estimates concerning them. As a compromise, the value of $z(0)$ is selected such that the developed country is initially twice as efficient as the developing country in abatement activities and, with the specification of $\beta_N(t)$ above, this gap will widen to three-fold in one hundred years unless the technological transfer is provided. Additionally, by supposing $\delta = 0.5$, we assume a quadratic function to describe the adjustment cost for augmenting the abatement efficiency in the developing country at each time-instant. The value of α is selected arbitrarily and, therefore, we will test the robustness of our simulation results with respect to its variation.

Moreover, while we first choose $l = 0.5$ and later change this value in order to observe its impact,

---

[28]The first and the second terms on the right hand side respectively signify the uncontrolled emission rates of the developed and developing countries. In this simulation, we implicitly assume that the growth rates of uncontrolled emissions are proportional to the expected economic growth rates of respective countries.

σ is fixed at one throughout this simulation because the abatement quota given by $a_N^Q(t)$ in (16) at σ = 1 turns out to be fairly comparable in scale, although slightly more stringent, to the abatement mandates that developed nations have agreed for the period of 2008-2012 in the Kyoto protocol. As is easily expected, a greater value of σ will benefit the developing country but harm the developed country. However, the variation of σ does not cause a significant qualitative change in the results of our simulation as long as it does not make $a_N^C(t)$ smaller than $a_N^N(t)$ at any moment.[29]

As a benchmark scenario, we examine a situation where there is no transfer program. We refer to such a situation as case *Q* (the case with the abatement quota and no transfer). Besides this benchmark case, we simulate the analytical results of the previous section. They are respectively called case *A* (the case with an AIJ-type transfer program), and case *C* (the case with a CDM-type transfer program).[30] In addition, we consider a situation where the implementation of not only a transfer but also an abatement quota upon the developed country is infeasible. This case (denoted by case *N*) would represent a "pre-Kyoto" situation now that developed nations have committed to their abatement quotas. Therefore, we will consider this case only as a reference, in terms of scaling the paths of significant variables in the three cases above, and not as a plausible scenario.

Now, we turn to the results of our simulation. Figure 1 presents the equilibrium path of the economic transfer ratio, $\gamma(t)$, over a hundred-year horizon. The economic transfer is provided in both cases *A* and *C*, but the time-paths of $\gamma(t)$ are different between these two cases owing to the

---

[29] If $a_N^C(t)$ were smaller than $a_N^N(t)$, there would be some superfluous abatement credits with the CDM.

[30] In cases *A* and *C*, the developed country is able to choose the initial level of the technological transfer so that the time-path of $T(t)$, which is specified by (35), will minimize its own total costs over the planning horizon. Of course, this equation alone does not specify the equilibrium value of $T(0)$. In order to derive $T(0)$ analytically we must impose the transversality condition in addition to (35). In this paper, however, we adopt another procedure in deriving $T(0)$, instead of imposing the transversality condition directly. We roughly approximate such a value of $T(0)$ through trials and errors in the sensitivity-analysis mode included in a computer software called STELLA. The selection of $T(0)$ in the equilibrium is based on the welfare comparison of the developed country for the first 150 years, but this particular choice of a time-horizon does not lead to a significant qualitative change in the results of our simulation.

presence of the abatement credit system in case *C*. The entire path of $\gamma^C(t)$ lies significantly higher than that of $\gamma^A(t)$.[31] This result is quite intuitive because the credit system enables the economic transfer to benefit the developed country not only by encouraging abatement activities in the foreign country but also by allowing it to reduce the domestic abatement expense through credit acquisition. Although the time-path of $\gamma(t)$ gradually declines over time in both cases, its high value throughout the horizon implies that a considerable share of abatement efforts in the developing country will be financed by the developed country.

Figure 2 shows how the technological transfer is provided over time in cases *A* and *C*. The equilibrium paths of $T(t)$ in cases *A* and *C* start, respectively, at 1.0 and 2.0, and, after the gradual increase in the first 30 years or so, they start to decline and eventually reach zero in another some 30 years. It indicates that the developed country tries to lower $\beta_S(t)$, which is the abatement efficiency of the developing country, not immediately but rather gradually to the most desirable time-path from its own standpoint. As a result of this technological-transfer provision, $\beta_S(t)$ declines more dramatically in cases *A* and *C*, compared to case *Q*, where no transfer is available, as is presented in Figure 3. Generally, the technological transfer is supplied in greater quantity across time in case *C* than in case *A*. In fact, the introduction of the credit system in case *C* results in completely erasing the difference of the abatement efficiencies between the developed and the developing countries, i.e., $z(t) = 0$, when the supply of the technological transfer is finally ceased. This would be due to the extra incentive created by the credit system for the developed country to lower the time-path of $\beta_S(t)$.

Figure 4 depicts the equilibrium paths of the abatement in the developing country for respective cases, including case *N*. In this simulation, the time-paths of $a_S(t)$ are gradually increasing in all the

[31] A superscript beside a variable signifies its equilibrium value in each case.

four cases. In the presence of a transfer program, the developing country determines the level of $a_S(t)$ at each instant, after observing the selections of $\gamma(t)$ and $T(t)$ by the developed country. The provision of both the economic and technological transfers in cases *A* and *C* raises the equilibrium path of $a_S(t)$ significantly. The economic transfer works directly through the increase of $\gamma(t)$ to raise $a_S(t)$ whereas the technological transfer indirectly induces the increase of $a_S(t)$ through a smaller $z(t)$, i.e., narrowing the gap between the abatement efficiencies of the two countries. The introduction of the credit system in case *C* significantly raises the overall path of $a_S(t)$, in comparison with case *A*. Given the composition of equation (27), this indicates that the influences of a greater $\gamma(t)$ and a smaller $\beta_S(t)$ $(= \beta_N(t) + z(t))$ in case *C* overwhelm the effect of l (> 0) on the selection of $a_S(t)$ by the developing country. The effect of the credit mechanism upon $a_S(t)$ in case *C* will be discussed further in relation to the impacts of the parameter l. Figure 5 presents the time-paths of the abatement in the developed country. This figure shows that the credit mechanism in case *C* eases its abatement burden to a certain extent, but not completely.

The results on these important variables above are combined to yield the time-paths of the atmospheric CO_2 stock in four respective cases, including case *N*. Figure 6 shows that case *A* achieves the most notable slowdown in the CO_2 stock increase, followed by case *C*, case *Q*, and, finally, case *N*. The presence of the credit mechanism in case *C* slightly raises the pollutant stock path compared to case *A*, but it still achieves a significantly lower stock level than in case *Q* where no transfer is available.

Another intriguing result of this simulation can be observed in the welfare consequences of the three plausible scenarios, i.e., case *Q*, case *A* and case *C*. Table I lists the approximate values of the objective functions during the first 150 years for the two countries. Obviously, a smaller value is preferred since the goal of each country would be to minimize its own total costs. The numbers within the parentheses in Table I signify the order of preference for each country. It shows that the developing country likes case *C* best, followed by case *A*, and, case *Q*. The developed country also prefers case *C* most, followed by case *A*, and, finally, case *Q*. Hence, both countries favor the welfare result of case *C* over that of case *A*. Interestingly, the developing country prefers case *C* to case *A*, in spite of the fact that some developing nations are still hesitant about the introduction of a credit-based transfer program. Our simulation result suggests that the developing country would be better off by welcoming the credit-based transfer program, which, in fact, holds true for wide ranges of σ and l. It follows that, once the developed country agrees to commit itself to such an abatement quota as we have assumed above, both of them might be best off by simultaneously institutionalizing an environmental-transfer program with an appropriate abatement-credit system.

The effect of different values of l is particularly intriguing since it reflects the scale of implementing the credit-system, which is still subject to future intergovernmental negotiations. Figure 7 describes the economic transfer ratio in case *C* where the value of l varies from its original value, 0.5, to 0.3 and to 0.7. As it shows, a larger l induces a greater economic transfer ratio because the increase in the amount of abatement credits that the developed country can receive makes the economic transfer more attractive to this country. On the other hand, Figure 8 indicates that the variation of l does not have a significant impact on the provision of the technological transfer. This implies that the time-path of $\beta_S(t)$ will not be affected very much by a variation of l.

The abatement level of the developing country in case *C*, which is determined by (27), is influenced by the values of both $\gamma(t)$ and l. Since a greater l significantly raises the value of $\gamma(t)$, in addition to its direct effect of discouraging the abatement in the developing country, the overall effect of a change in l upon the equilibrium time-path of $a_S(t)$ is ambiguous. Figure 9 depicts its equilibrium paths for the three different specifications of l. The level of $a_S(t)$ tends to get smaller with an increase in l, especially during later years. This implies, in this particular simulation, the direct effect of a greater l upon $a_S(t)$ overwhelms its indirect effect through $\gamma(t)$, resulting in a lower equilibrium path of $a_S(t)$. This result indicates that the developing country quite rationally remains cautious of the amount of abatement credits acquired by the developed country and respond to the high level of l by lowering the level of its own abatement.

Figure 10 and Figure 11 respectively present the changes in the abatement level of the developed country and the CO_2 stock level with respect to the variation of l. They show that the variation of l affects the abatement level of the developed country quite significantly through the credit acquisition, and that a greater l will translate into a higher equilibrium path of the pollutant stock due to the reductions in both $a_S(t)$ and $a_N(t)$.

Table II presents the total costs of the two countries in these three cases. Although not by a significant margin, each country prefers a different value of l among the three values considered here. Whereas the developing country prefers l = 0.3, the developed country likes l = 0.7 best among these three values. This preference conflict over the value of l suggests that the determination of l, as well as the determination of σ which we did not address in this simulation, would likely be a subject of international negotiations. However, the developing country would not accept the institutionalization of the credit system at l = 0.7, because it would be worse off with its implementation, compared to the welfare result in case *A*. In such a case, the developed country might consider offering a lump-sum side payment, besides the economic transfer, to the developing country in order to implement a high value of l.

According to the sensitivity analysis with respect to the value of α, the simulation results above are rather sensitive to its variation. In particular, α affects the time-path of the technological transfer to a significant extent. Since the increase in α raises the effectiveness of the technological transfer, a greater value of α leads to a higher path of $T(t)$ and results in a faster decline of $\beta_S(t)$.

5. Summary and Extension Possibilities

Here, we briefly summarize the several implications obtained from our simulation results, regarding the provisions of environmental transfers and the impact of introducing an abatement credit system. Because of the simplifications and the assumptions made here, and due to the great uncertainty surrounding the issue of global warming, our simulation results should be seen as only indicative. However, they do provide some insights into general tendencies and may help in understanding the roles and effects of environmental transfer programs and, especially, an abatement credit system.

Unlike an economic transfer that is continuously provided over the entire horizon, a technological transfer is applied in a relatively concentrated fashion across time. However, our simulation also implies that the developed country tries to lower the abatement efficiency of the developing country rather gradually, not instantaneously, to the most desirable time-path from its own standpoint. As expected, the introduction of credit system further encourages the provisions of both economic and technological transfers. In our study, economic and technological transfers respectively contribute to the increase in the abatement level of the developing country. Furthermore, the introduction of the credit system can strengthen these complementarities.

Meanwhile, the establishment of the abatement credit system does not affect the total CO_2 abated by the two countries too dramatically in our particular simulation. This is because, with the credit system, the recipient country would also become concerned about the loss from the reduced abatement in the developed country. On the other hand, the credit mechanism eases the abatement burden of the developed country, although not completely. As for its impact on the pollutant stock, the presence of the credit system leads to a slightly more rapid increase in the stock level than in the case of the quota alone, but it still induces a lower equilibrium path than in a situation where a transfer is not available.

Most importantly, our simulation results indicate that, for a certain range of *l*, a credit-based transfer program can be more beneficial not only for the donor country but also for the recipient country in comparison with a non-credit-based transfer program. Therefore, once the developed country agrees to commit itself to the abatement quota of the nature discussed above, both of them might be better off by implementing an appropriate credit-based transfer program concurrently. In other words, the credit-based transfer program could be a Pareto-improving policy instrument from a non-credit-based transfer program under certain conditions. This would be because, with a credit system, the donor country increases the provisions of both economic and technological transfers and their benefits overwhelm the loss to the recipient country from a reduction in the donor country's abatement. However, as the "credit conversion" ratio, *l*, goes up, the recipient country becomes increasingly cautious about the excessive acquisition of abatement credits by the donor country.

Given the significant scientific and economic uncertainty surrounding global warming (Bolin (1998)) and the nature of CO_2 abatement activities which usually seem to involve sunk costs, the issue of irreversible decision-makings under uncertainty should play an increasingly important role in the literature. Regarding these this topic, we could build future researches upon the works by Kolstad (1996), Conrad (1997) and Pindyck (2000). Moreover, with the international nature of this problem, it would be more desirable to incorporate such an issue into a game-theoretic framework. The study by Xepapadeas (1998), which examines an optimal-stopping rule problem in the context of a stochastic differential game, would be one of the initial attempts in this area. The economic implications of an environmental transfer program is yet to be explored in such a framework.

References

Arrow, K. and M. Kurz (1970), *Public Investment, the Rate of Return, and Optimal Fiscal Policy*, Baltimore, MD: Johns Hopkins University Press.

Basar, T. and G. Olsder (1995), *Dynamic Noncooperative Game Theory*, *2nd Edition*, London: Academic Press.

Bolin, B. (1998), 'Key Features of the Global Climate System to Be Considered in Analysis of the Climate Change Issue', *Environment and Development Economics* **3**: 348-365.

Braden, J. and D. Bromley (1981), 'The Economics of Cooperation over Collective Bads', *Journal of Environmental Economics and Management* **8**: 134-150.

Cesar, H. (1994), *Control and Game Models of the Greenhouse Effects*, Berlin: Springer-Verlag.

Cline, W. (1991), 'Scientific Basis for the Greenhouse Effect', *The Economic Journal* **101**: 904-919.

Conrad, J. (1997), 'Global Warming: When to Bite the Bullet', *Land Economics* **73**: 164-173.

Dockner, E., S. Jorgensen, N. van Long and G. Sorger (2000), *Differential Games in Economics and Management Science*, Cambridge, U.K.: Cambridge University Press.

Falk, I. and R. Mendelsohn (1993), 'The Economics of Controlling Stock Pollutants: An Efficient Strategy for Greenhouse Gases', *Journal of Environmental Economics and Management* **25**: 76-88.

Farzin, Y. (1996), 'Optimal Pricing of Environmental Natural Resource Use with Stock Externalities', *Journal of Public Economics* **62**: 31-57.

Fershtman, C. (1987), 'Identification of Classes of Differential Games for which the Open Loop is a Degenerate Feedback Nash Equilibrium', *Journal of Optimization Theory and Applicatio*ns **55**, 217-231.

Gjerde, J., S. Grepperud, and S. Kverndokk (1999), 'Optimal Climate Policy under the Possibility of a Catastrophe', *Resource and Energy Economics* **3-4**: 289-317.

Hoel, M. (1991), 'Global Environmental Problems: The Effects of Unilateral Actions Taken by One Country', *Journal of Environmental Economics and Management* **20**: 55-70.

Houghton, J., B. Callander, and S. Varney (1992), *Climate Change: The Supplementary Report to the IPCC Scientific Assessment*, Cambridge, U.K.: Cambridge University Press.

IPCC (1990), *Climate Change: The IPCC Scientific Assessment*, Cambridge, U.K.: Cambridge University Press.

IPCC (1996), *Climate Change 1995: The IPCC Second Assessment Report*, Cambridge, U.K.: Cambridge University Press.

Karp, L. and X. Liu (2000), 'The Clean Development Mechanism and Its Controversies', Department of Agricultural and Resource Economics and Policy Working Paper No. 903 (University of California at Berkeley).

Kolstad, C. (1996), 'Learning and Stock Effects in Environmental Regulation: The Case of Greenhouse Gas Emissions', *Journal of Environmental Economics and Management* **31**: 1-18.

Maler, K. and A. de Zeeuw (1998), 'The Acid Rain Differential Game', *Environmental and Resource Economics* **12**: 167-184.

Mehlmann, A. (1988), *Applied Differential Games*, New York, NY: Plenum Press.

Michaelis, P. (1994), 'The Cost of Stabilizing the Atmospheric Concentration of Greenhouse Gases', Paper presented to the workshop, Designing Economic Policy for Management of Natural Resources and the Environment, Rethymno, Greece.

Michaelis, P. (1999), 'Sustainable Greenhouse Policies: the role of non-CO_2 gases', *Structural Change and Economic Dynamics* **10**: 239-260.

Mino, K. (2000), 'On Time Consistency in Stackelberg Differential Games', mimeo (Kobe University).

Nordhaus, W. (1991), 'To Slow or Not to Slow; The Economics of the Greenhouse Effect', *The Economic Journal* **101**: 920-937.

Nordhaus, W. (1994), *Managing the Global Commons*, Cambridge, MA: The MIT Press.

Petit, M. (1989), 'Fiscal and Monetary Policy Co-ordination: a Differential Game Approach', *Journal of Applied Econometrics* **4**: 161-179.

Pindyck, R. (2000), 'Irreversibilities and the Timing of Environmental Policy', *Resource and Energy Economics* **22**: 233-259.

Tahvonen, O. (1994), 'Carbon Dioxide Abatement as a Differential Game', *European Journal of Political Economy* **10**: 685-705.

van Aarle, B., L. Bovenberg and M. Raith (1995), 'Monetary and Fiscal Policy Interaction and

Government Debt Stabilization', *Journal of Economics* **2**: 111-140.

van der Ploeg, F. and A. de Zeeuw (1992), 'International Aspects of Pollution Control', *Environmental and Resource Economics* **2**: 117-139.

Xepapadeas, A. (1998), 'Policy Adoption Rules and Global Warming', *Environmental and Resource Economics* **11**: 635-646.

Xie, D. (1997), 'On Time Inconsistency: A Technical Issue in Stackelberg Differential Games', *Journal of Economic Theory* **76**: 412-430.

Yamin, F. (2000), 'Joint Implementation', *Global Environmental Change* **10**: 87-91

de Zeeuw, A. and F. van der Ploeg (1991), 'Difference Games and Policy Evaluation: A Conceptual Framework', *Oxford Economic Papers* **43**: 612-636.

Tables and Figures

	The Developing Country (*S*)	The Developed Country (*N*)
Case *Q*	1072.3 (3)	5338.1 (3)
Case *A*	1028.5 (2)	5284.3 (2)
Case *C*	1027.8 (1)	4869.6 (1)

Table I. The welfare value during the first 150 years
(Numbers are in billion dollars. Numbers in parentheses are rankings.)

	The Developing Country (*S*)	The Developed Country (*N*)
$l = 0.3$	1022.2 (1)	5024.3 (3)
$l = 0.5$	1027.8 (2)	4869.6 (2)
$l = 0.7$	1033.8 (3)	4757.5 (1)

Table II. The welfare value with the variation in *l*
(Numbers are in billion dollars. Numbers in parentheses are rankings.)

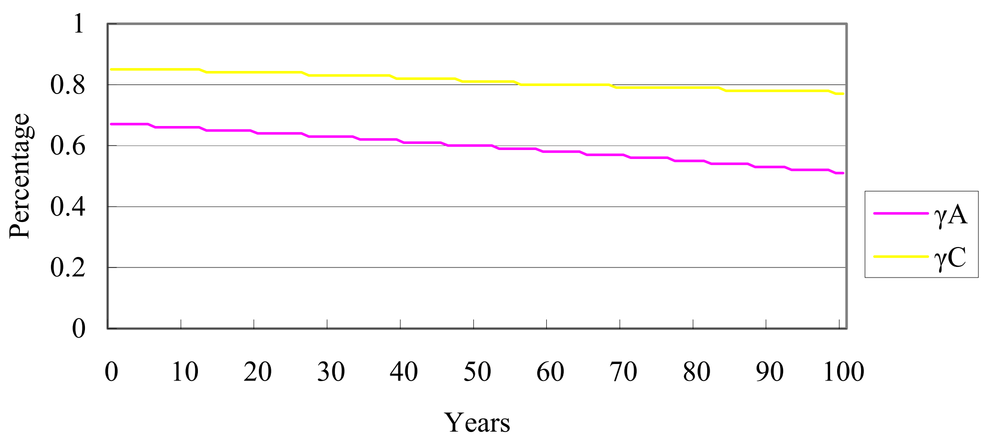

Figure 1. The equilirium path of the economic transfer ratio

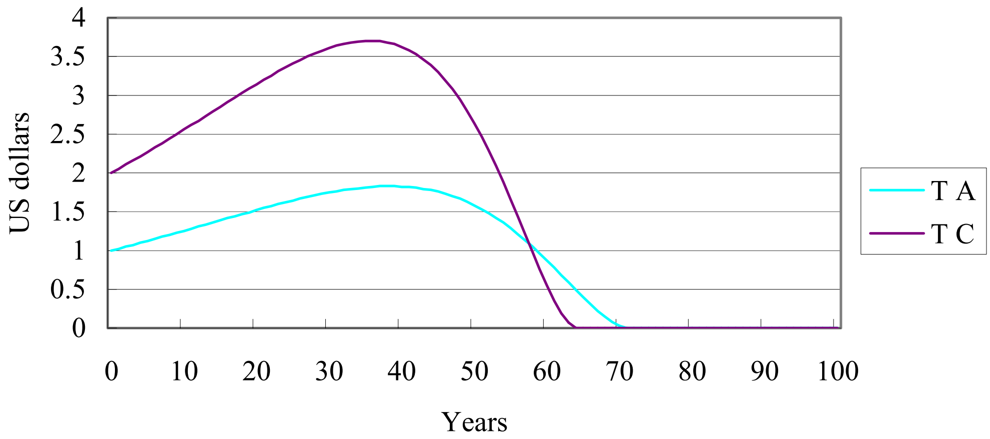

Figure 2. The equilirium path of the technological transfer

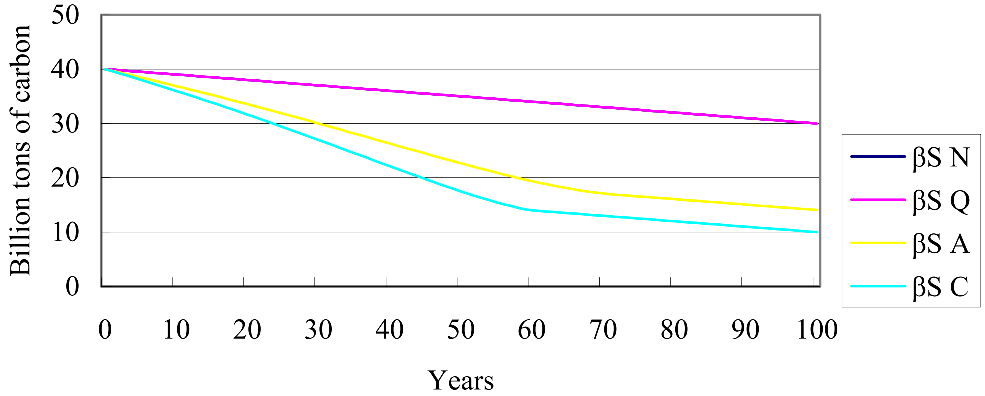

Figure 3. The path of the abatement efficiency parameter in the developing country

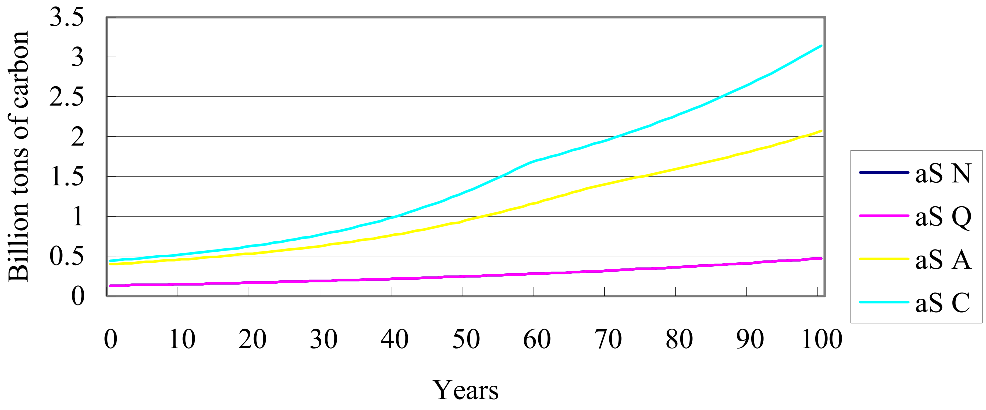

Figure 4. The equilibrium path of the emission abatement in the developing country

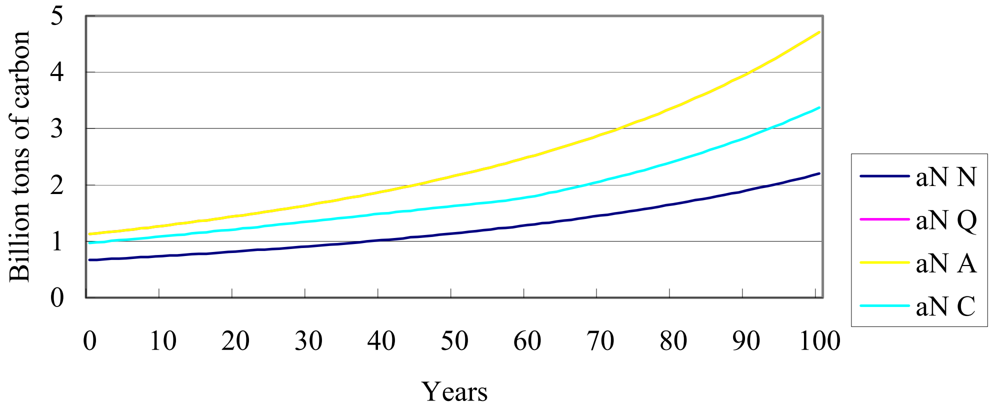

Figure 5. The equilibrium path of the emission abatement in the developed country

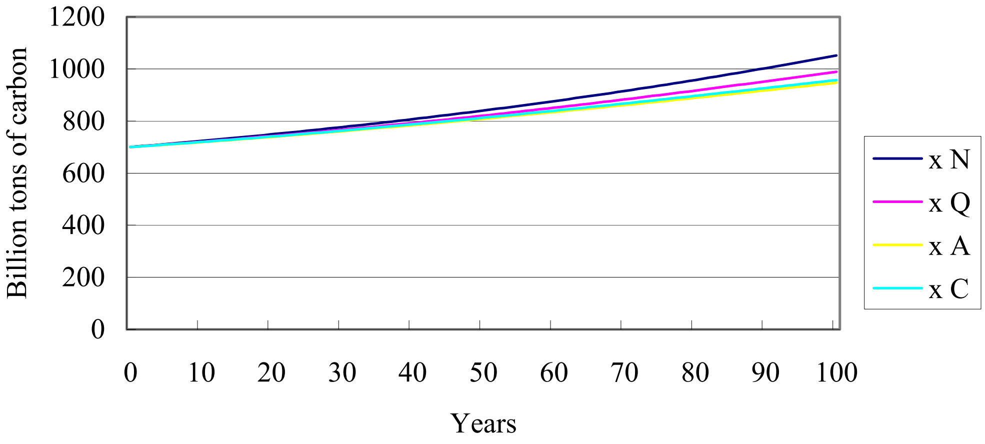

Figure 6. The time path of the atmospheric CO2 stock

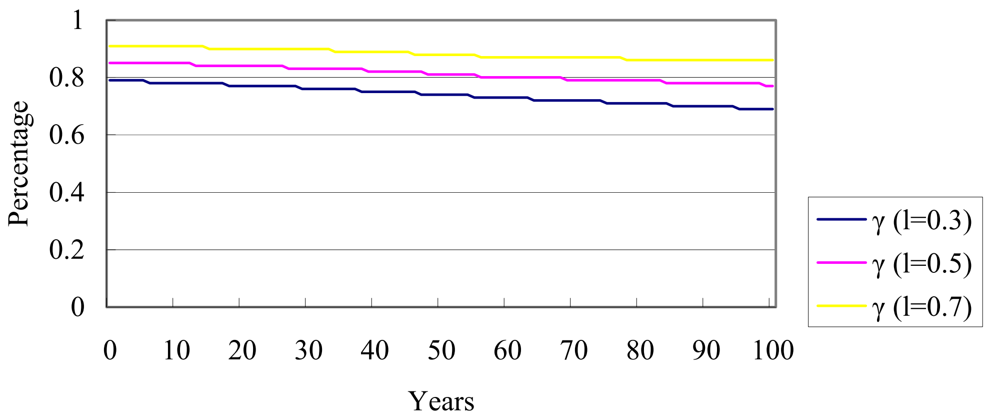

Figure 7. The path of the economic transfer ratio with the variation in l

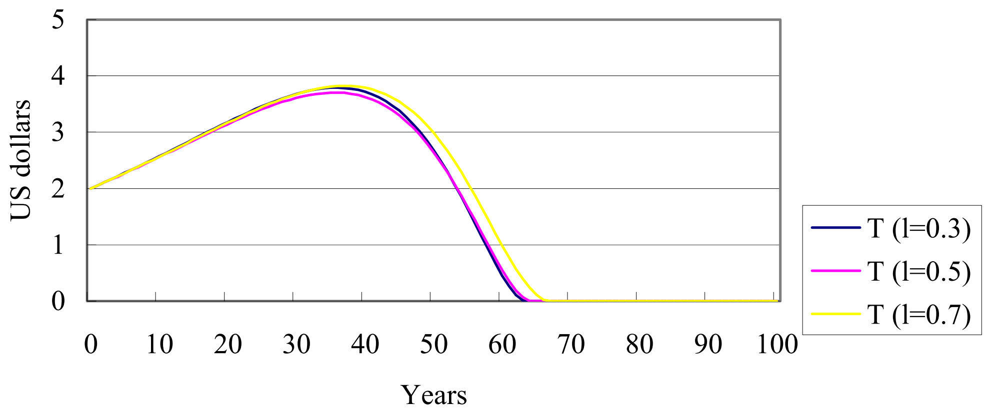

Figure 8. The path of the technological transfer with the variation in l

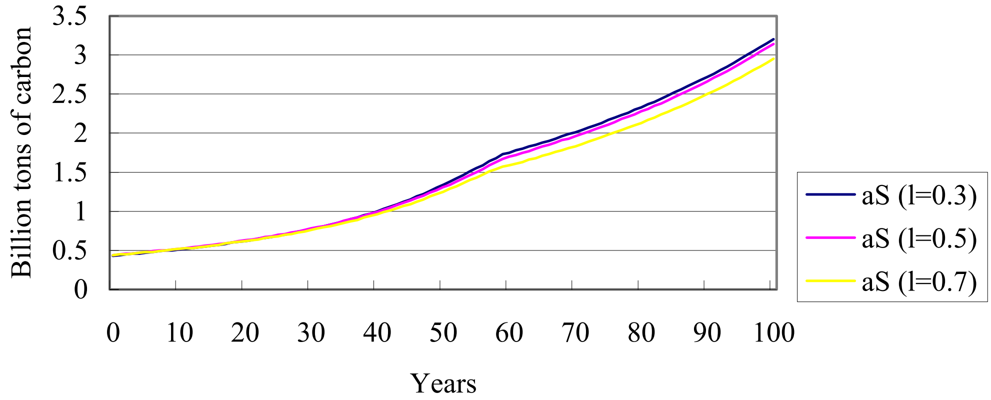

Figure 9. The path of the emission abatement in the developing country with the variation in l

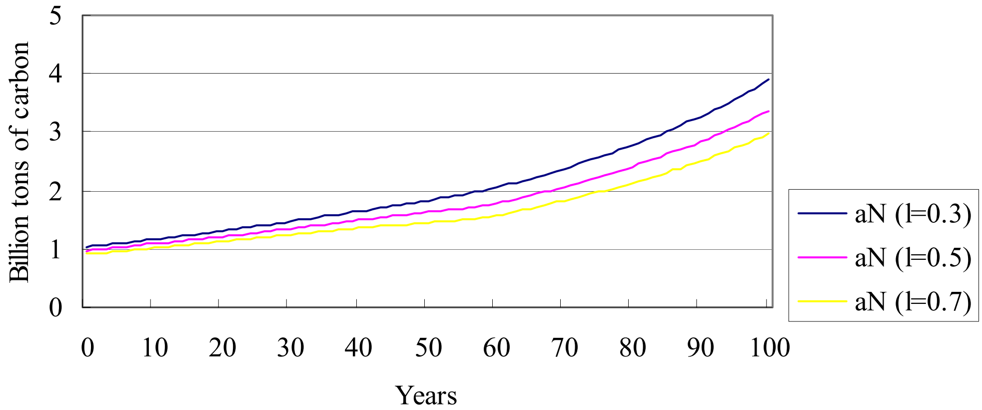

Figure 10. The path of the emission abatement in the developed country with the variation in l

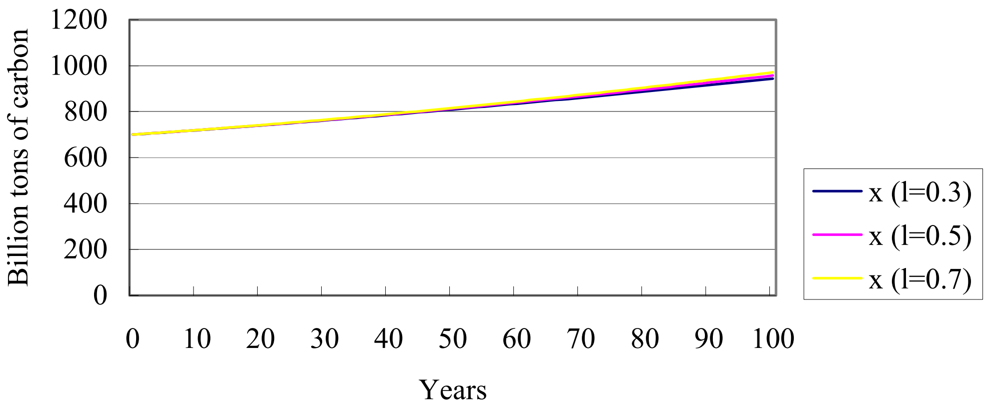

Figure 11. The path of the atmospheric CO2 stock with the variation in l