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On Vulnerability of International Cooperation to Slow Global Warning*

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1. Introduction

There is to date a rapidly growing number of literature that assesses either by theoretical analyses or by numerical simulations the outcome of the international policy coordination towards reducing and stabilizing CO_2 emissions[1]. One notable common presupposition shared by most such studies is that they assume full participation in the international CO_2 treaties by all countries and regions under the global commons, implying that the abatement of CO_2 emissions and slowing global warming are the consensus objectives of every country. Whilst such a situation is no doubt an ideal prerequisite to an effective international cooperative action, full participation in reality may be a bit too optimistic (e.g., Kverndokk (1994)). In fact, the purpose of this study is to evaluate the structural vulnerability of conditions which lead to concluding the international CO_2 treaties. In other words, relying on virtual simulations of a worldwide climate-economy model we shall assess how robust the international cooperative action can be against the various factors that disturb the global CO_2 coalition.

Needless to say the benefits from CO_2 emissions materialize immediately and accrue to each emitting country ; the larger the CO_2 emissions the higher the production activities and thereby the level of consumption. On the other hand, the damages of CO_2 emissions fall on all countries and last as long as the CO_2 remains in the atmosphere. Therefore, net gains (benefits minus costs) of an individual country depend not only on its own choice of CO_2 emissions but also on how the rest of the world act at the same time, thus necessitating for each individual country to take strategic decisions. It is natural that as long as a country's net gains from reducing CO_2 emissions are on the positive side, she has an incentive to participate in and stay within the international CO_2 treaties. However, if on the contrary the relevant net gains are on the negative side, a rational sovereign country will not join the coalition that binds her to abate CO_2 emissions. Yet even in that case, if side payments are to flow from gaining countries to losing countries as compensations, international CO_2 treaties can be signed by all countries provided that the worldwide net gains as a whole of reducing CO_2 emissions are positive.

Then, even without relying on any theorem of game theory or any proposition of environmental economics, it is straightforward that the outcome of resource allocation under a cooperative decision making Pareto-dominates that under any noncooperative decision making if only the decision is made free of compulsion. This implies that from the social optimum point of view the international CO_2 treaties must be signed by all countries and regions under the global commons, resulting in the socially efficient abatement of CO_2 emissions.

However, recent development of the game theory has revealed that cooperative behaviors are not necessarily sustained as an equilibrium under decentralized decision makings. In particular it is well known that there is an incentive for each economic agent to free ride in enjoying the services of common property, thus resulting in an over utilization and consumption of them. This failure of coordination has been known as the tragedy of commons (Hardin (1968)) or called the prisoners dilemma Nash equilibrium within the framework of noncooperative games. The case of reducing global CO_2 emissions is no exception and in fact most sovereign countries and regions have not so far introduced effective measures to abate CO_2 emissions even having signed a preparatory agreement at the 1992 Rio conference. Thus every country (except possibly for Nordic countries) appears to be taking advantage of being a free rider.

Moreover Welsch (1993) emphasizes two kinds of difficulties which become important in the actual process of reaching agreement. First while it is the overall abatement of CO_2 emissions that eventually matters to global warming, in reality abatement duties must be allocated to each of the participating countries. Negotiations centering around the allocation rule, including the direction and amount of side payments, may become the crucial concern of would-be participating countries. Each country would attempt to press for her interests depending on her bargaining power. The second and related difficulty is that so far no international authority exists to enforce an allocation and payment scheme, indicating that individual rationality instead is crucial for any arrangement of the international CO_2 treaties.

With these difficulties in mind, it is noteworthy for us to ask on what conditions will the international CO_2 treaties be signed cooperatively by all countries and regions. Especially we are interested in how the countries which differ in the stages of economic development, number and composition of population, geographical features, technology, preferences, and so forth arrive at an eventual coordination. Stimulated by essentially the same determination Asako, Kuninori, and Matsumura (1995)——hereinafter AKM for short——have investigated, within the solution concept to the Nash bargaining game, the optimal feature of carbon taxes for and side payments between participating countries. Although the study of AKM (1995) has given certain insights, it is limited to theoretical propositions under an abstract set of assumptions. The shortcomings of AKM (1995) include, among others, its dependence on the static framework abstracting from both economic growth and long lived effects of CO_2 emissions on global warming. Thus the present study is in a sense an extension of AKM (1995) towards two directions. One is the introduction of the dynamics of economic growth and CO_2 concentration in the atmosphere. The other is an inclusion of simulation analyses to gauge numerically the significance of efficient economic and climatic responses to various exogenous shocks to the economy. For this purpose we utilize a variant of the DICE model developed by Nordhaus (1994).

The rest of the present paper is structured as follows. In Section 2 we discuss the basic theoretical framework for the cooperative action in reducing CO_2 emissions along the line of a dynamic cooperative game. The model developed here is just an heuristic one and it attempts to capture only the basic feature of the DICE model. Namely, optimal intertemporal resource allocation as a solution to dynamic optimization in the light of global warming constitutes the main framework of our model. Meanwhile we extend the DICE model towards an important direction in that we introduce more than one decision makers. In this section, some of the obtained implications of the model analysis are discussed as well.

Sections 3 and 4 are devoted to simulation analyses. In section 3 we describe the assumptions of the simulation analyses. The DICE model is modified by decomposing the entire world into two aggregated and distinct regions; these are industrialized countries and developing countries. We explain how this decomposition is carried out. Section 4 reports the simulation results which obtain under various set of assumptions. Industrialized countries and developing countries are assumed similar in many respects but assumed at the same time crucially different with respect to the future courses, as well as the initial levels, of population and technologies. We also control and assume different setup for the bargaining power and discount rate of each aggregated countries. Alternative features of cooperation with and without side payments are also examined. Section 5 concludes the paper with some remarks.

2. Conditions for International Cooperation

In this section, we briefly describe the basic framework within which we examine the conditions for the international cooperation towards slowing global warming.

2.1 Individual Country

A country i at time t attempts to maximize the discounted sum of intertemporal utility $U^i(t)$ over the infinite time horizon,

$$U^i(t) = \int_t^\infty e^{-\rho_i(s-t)} u^i(c_{is}, L_{is})\, ds \qquad (1)$$

where c_{it}, and L_{it}, denote, respectively, per capita consumption and population. The instantaneous utility function exhibits decreasing marginal utilities and the Inada condition with respect to consumption and, possibly, the unitary elasticity with respect to population whose future path is given exogenously, independent of both economic and climatic conditions. The parameter $\rho_i \geqq 0$ represents the pure rate of time preference of which we allow for different values for different countries.

Output Y_{it} is related positively with capital K_{it} and labor L_{it} (synonymous with population) with decreasing marginal productivity and negatively with the concentration of CO_2 in the global atmosphere M_t which directly damages productivity of all countries. Then, denoting by A_{it} the exogenously given total factor productivity (exclusive of the negative contribution of M_t), we can write

$$Y_{it} = A_{it}\Omega^i(M_t)F^i(K_{it}, L_{it}), \qquad (2)$$

where we assume $\Omega^i_M = d\Omega^i/dM < 0$ and $\Omega^i_{MM} < 0$ The expression $F^i(K_{it}, L_{it})$ means a standard neoclassical constant-returns-to-scale production function with the Inada condition. As for the expenditure side we abstract from the government sector and international trade but take account of side payments among countries, so that we have

$$Y_{it} = C_{it} + I_{it} + q^i(B_{it}) + S_{it}, \qquad (3)$$

where C_{it}, I_{it}, and S_{it} denote, respectively, consumption $C_{it} = c_{it}L_{it}$, investment, and net side payments flowing out from the home country i. The third term on the right hand side equals the forgone costs of reducing CO_2 by the amount B_{it}, We assume increasing marginal costs,

$$q^i_B > 0,\ q^i_{BB} > 0.$$

The dynamics is characterized by two differential equations. First capital accumulation obeys,

$$\dot{K}_{it} = I_{it} - \delta_i K_{it} \qquad (4)$$

where a dot "." denotes the total derivative with respect to time t, and δ_i denotes the depreciation rate of capital. Second the evolution of atmospheric concentration of CO_2, M_t, is given by

$$\dot{M}_t = \sum_i (1-\mu_{it}) E_{it} - vM_t \tag{5}$$

where CO_2 emissions E_{it} are progressively related with output,

$$E_{it} = E^i(Y_{it}), \tag{6}$$

with $E^i_Y>0$, $E^i_{YY}>0$ The variable μ_{it}, denotes the emission control rate which must satisfy an identity

$$B_{it} = \mu_{it}E_{it}. \tag{7}$$

The constant parameter ν represents a natural assimilation rate of the existing CO_2 concentration.

To sum up, country i's problem is as follows. She attempts to maximize, for given initial conditions of two state variables K_{it} and M_t the discounted sum of utilities (1) by optimally choosing the current and future path of capital accumulation and the emission control rates. Throughout we may assume, at least at a theoretical level, that no uncertainties are involved about the structure of the economy and the current and future paths of exogenous variables such as population and total factor productivity. However, this is not sufficient for country i to determine the perfect foresight path because, if she solves this problem noncooperatively, she faces another kind of indetermination. Namely she must choose her optimal strategy by considering the strategies of the other countries, each one of which in turn is dependent on the strategies of countries other than herself including the country i. As we noted earlier in Section 1, a possible equilibrium of such a noncooperative game is that of Nash in which global warming is not taken care of because of every country's simultaneous longing to be a successful free rider.

2. 2 Efficient Cooperative Solution

One of the most frequently referred equilibrium concepts of cooperative games is the Nash bargaining solution (Nash (1950, 1953)). If for simplicity there were only two countries, the Nash bargaining solution at time t is the one which maximizes the expression

$$(U^1(t)-\bar{U}^1(t))(U^2(t)-\bar{U}^2(t)) \tag{8}$$

by optimally choosing at a time the strategy set of both countries subject to the constraints (2), (3), (4), (6), (7) for $i=1, 2$ and (5) and the budget constraint of side payments,

$$S_{1t}+S_{2t} = 0, \tag{9}$$

where $U^i(t)$ denotes the maximum level of country i's payoff or utility (1) when she (and the other countries) choose noncooperative strategies.

It is well known that the Nash bargaining solution is one of the equilibria in which resources are utilized socially efficiently and thereby is Pareto optimum. Usually as in (8) the Nash bargaining solution allots equal weights to each player's bargaining power, which is represented by the net utility gains from coordination. In that sense, the Nash bargaining solution is regarded as a special case as each country's bargaining power in general may vary depending on idiosyncratic factors. In what follows, therefore, we allow for more general form of cooperation by incorporating various Pareto optimum solutions. To do so we only set various weights $\alpha>0$ in the following maximand which replaces (8),

$$U^1(t)+\alpha U^2(t). \tag{10}$$

To sum up, alternative cooperative solutions are those that maximize (10) for various α subject to the constraints (2), (3), (4), (6), (7) for $i=1, 2$ and (5), (9) and the initial conditions of two state variables, capital stock and the concentration of CO_2. Occasionally, we also obtain the constrained cooperative solution which does not allow side payments. After a series of routine and tedious calculations, we obtain that the first order conditions for the optimum include

$$\frac{u^1_c(c_{1t},L_{1t})}{u^2_c(c_{2t}, L_{2t})} = \alpha e^{(\rho_2-\rho_1)t}\frac{L_{1t}}{L_{2t}} \tag{11}$$

$$q^1_B(\mu_{1t}E_{1t}) = q^2_B(\mu_{2t}E_{2t}). \tag{12}$$

Condition (11) indicates that the ratio of marginal utilities of consumption between two countries equals the ratio of population, adjusted for the utility weight α and differences in the rates of pure time preference. Other things being equal, the greater the utility weight α and/or the pure rate of time preference of countries 2, the larger is its per capita consumption. A larger population reduces per capita consumption of that country. Condition (12) indicates that, if the cost functions of reducing CO_2 emissions are the same between two countries, the volume of abatements of CO_2 should also be the same. If we have formulated instead that the CO_2 abatement cost in equation (3) is a function of only the emission control rate, i.e., $q^i(\mu_{it})$, then $\mu_{it}=\mu_{2t}$ follows in the optimum. Note, however, that condition (12) is valid only when side payments are transferred as an interior solution.

3. Assumptions of Simulation

In this section, we describe basic assumptions in carrying out numerical simulations. As we noted in the previous sections, we adopt Nordhaus's DICE (the Dynamic Integrated model of Climate and the Economy) model for our starting point. The DICE model is basically a perfect foresight optimal growth model with a planning period of 400 years, with 10 years interval. What is attractive about the DICE model is that major economic and scientific elements regarding global warming are linked in a relatively simplified and tractable way to convey policy implications.

3.1 The DICE Model

The major achievement of the DICE model was to calculate the optimal path for both capital accumulation and GHG (greenhouse gas) emission reduction for the entire world. For this purpose, Nordhaus (1994) presented a concise set of interactions among the level of radiative forcing caused by the atmospheric accumulation of GHG and the temperature rises of atmosphere, the upper and deep oceans. Then, he selects the temperature rises of the atmosphere and upper oceans with damages and emission control efforts, which causes output losses. Faced with this set of environment, a representative consumer——multiplied by population——allocates its consumption activities optimally over 400 years.

One of the main policy conclusions of the DICE model by Nordhaus is that "massive effort to slow climate change today is premature given current understanding of the damages imposed by greenhouse warming" (Nordhaus (1994), p. 6.) However, at the same time, he warns that global circulation systems are incredibly complex so that, if scientific evidence indicates calamitous consequences are likely, a strenuous effort is necessary and the DICE model will help devise the scope and timing of policy responses.

As stated in Section 1, our interest here is not to evaluate the message of the DICE model *per se*[2]. We would instead like to numerically evaluate the potential vulnerability of cooperative actions against several small changes in surrounding conditions by employing the parameter sets of the DICE model.

Because the DICE model is a one-sector world model, we first divide the world into two aggregated regions, i.e., industrialized countries and developing countries. In what follows, we explain how this task was done.

3.2 Modification of Parameter Set

In dividing the world into two regions, ——the industrialized and developing countries,——we took a methodology to keep most of the parameters intact. Namely we allot the same parameter values to both of the two aggregated countries as those adopted in the original one world DICE model. However, we put due emphasis on the linking sector of economic activities and climatic changes. In this sense, in the DICE model, key exogenous factors influencing the production level are patterns of (i) populations, (ii) overall technology represented by the level of total factor productivity (TFP), and (iii) the autonomous emission reduction[3]. Although it is argued that geographical impacts caused by climate change would be very large, reliable estimates for those two regions are not available to authors. Therefore we simply adopt most of the DICE's parameter estimates of the world average to the two regions.

(1) Population

Our population estimates are based upon the projection by the United Nations (1992), in which world population is projected from 1950 through 2150 by major areas. We slightly changed the original regional groupings so that our categorization of industrialized countries includes Japan and Korea in addition to North America, Europe, Former Soviet Union, and Oceania. The rest is categorized as developing countries. Then, using the same technique as the DICE model, we extrapolate the growth path of population. In our estimate, the level of population of the developing countries keeps increasing in the 21st century and stabilize since then on while that of the industrialized countries stabilizes on entering the 21st century. See Figure 1.

(2) Technology

With respect to the technological factors, two alternative cases are considered. For both cases, we assign exactly the same technological parameters of the original DICE model to the industrialized countries, with an exception of the initial value of 1965 which needed special treatment. In 1965, initial values of total factor productivity (TFP) and capital stock for both industrialized and developing countries are calculated in such a way that their income weighted average equals those of the original DICE model. As is seen in Figure 2, the initial value of TFP of the industrialized countries is well above the counterpart of the original DICE model, while that of the developing countries is well below it.

Case 1 (CONTF, for CONverging TFP) is a case where the TFP of the developing countries gradually converges to that of the industrialized countries. This case may represent a case of smooth technological transfer from the industrialized countries to the developing countries. The catching-up of the developing countries is to materialize in the 21st century. With respect to the emission control technology, Case 1 corresponds to that where autonomous emission reduc-

Fig. 1 Level of Popuration and Labor

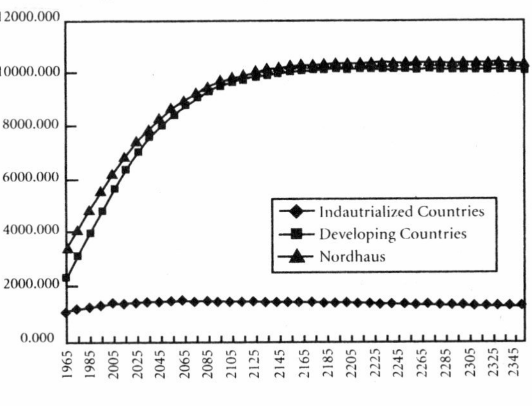


Fig. 2　Level of Total Productivity

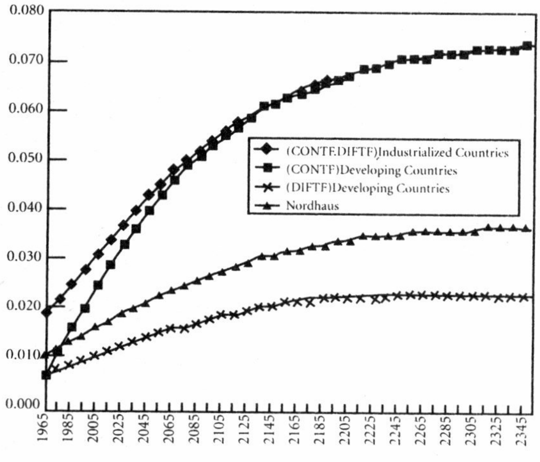
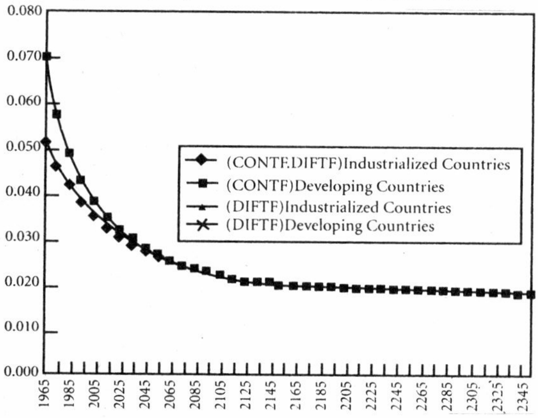


Fig. 3　CO_2-Equivalent-Emission Output Ratio



tion rate also converges to that of the industrialized countries since the initial value of emission control rate of the developing countries is set to 0.7 while that of the industrialized countries is 0.519. See Figure 3.

Case 2 (DIFTF, for DIFferent TFP) assumes that the same growth pattern of TFP follows for both of the two aggregated regions. Thus, the levels of total factor productivity never converge since their initial levels are different.

Although it is hard to imagine that, in 400 years, the technological gap never narrows or converges, we are also not certain when and what path a catching-up process will follow in the coming centuries. The most probable scenario in our simulation for technological prospect would well lie between Case 1 and Case 2.

4. Simulation Results

We carried out the following set of simulations for both cases : Case 1 (CONTF) and Case 2 (DIFP) We follow Nordhaus (1994) in that we are also interested in the future path of the economy up to the year 2105 because sometimes optimality requires subtle and unstable pattern of policy changes for the periods far away future from the present. The starting year is the present or 1995.

- Calculation of optimal utilities of industrialized and developing countries for different values of weight α.
- Alternative sets of discount rates between two regions.
- Size and pattern of side payments.

4. 1　Alteration of α

For Case 1 and Case 2, maximized values of each aggregated countries' utility levels are plotted as, respectively, in Figure 4 and Figure 5. In both cases, the shape of the utility frontier seems well behaved[4)].

For both cases, emission control rates of both of the regions are plotted for several α's, i.e., Figure 6 for Case 1 and Figure 7 for case 2. In general, emission control rate of the industrialized countries (Panel (a)) gets higher when α is larger or bargaining power of the developing countries gets larger. The general tendency is utterly opposite for the developing countries (Panel (b)). Moreover, in contrast to the emission control rates of the industrialized countries, those of the developing countries exhibit much larger variations.

A general implication is that those countries with smaller bargaining power need to reduce

Fig. 4

CASE 1. (CONTF) Maximized Utility Levels of Industrialized and Developing Countries for different α

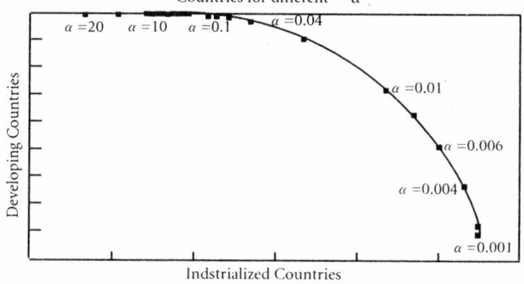


Fig. 5

CASE 1. (DIFTF) Maximized Utility Levels of Industrialized and Developing Countries for different α

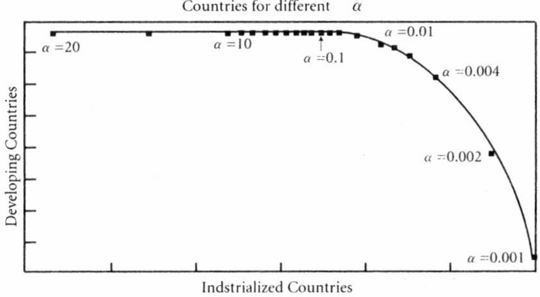
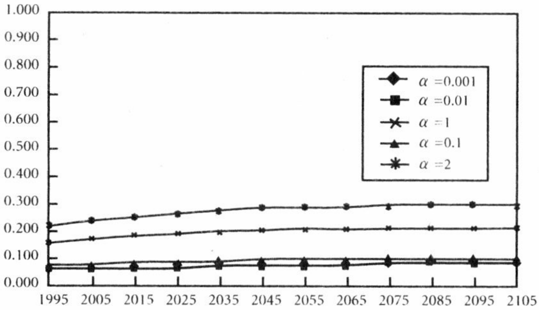


Fig. 6

(a) Case 1. (CONTF), Emission Control Rate: Industrialized Countries



(b) Case 1. (CONTF), Emission Control Rate: Developing Countries

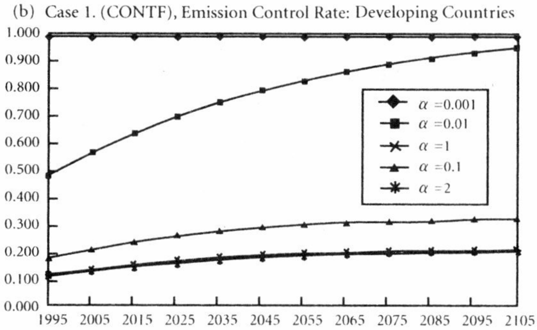
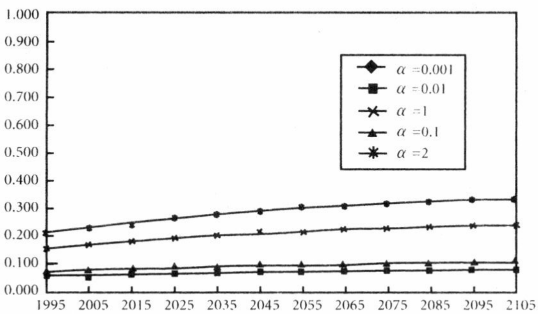
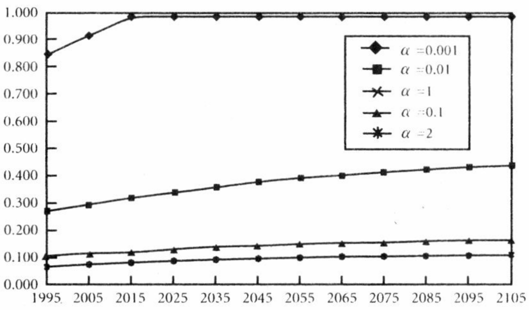


Fig. 7

(a) Case 2. (DIFTF), Emission Control Rate: Industrialized Countries



(b) Case 2. (DIFTF), Emission Control Rate: Developing Countries



CO_2 emissions to larger extent.

4.2 Alternative Sets of Discount Rates

Whether to discount the welfare of future generations has been an old philosophical and ethical question since at least Ramsey (1928) in the optimal growth literature. Following the equity oriented criterion of Rawls (1971), the problem of discounting has attracted revived concern in the 1970s especially in the field of exhaustible resources and environmental pollution (e.g., Solow (1974) and Asako (1980)). This concern is further amplified in relation to the problem of global warming. Nordhaus (1994) discusses in detail the consequence of applying different discount rates within the DICE model and asserts why the appropriate annual discount rate should equal 3 percent[5].

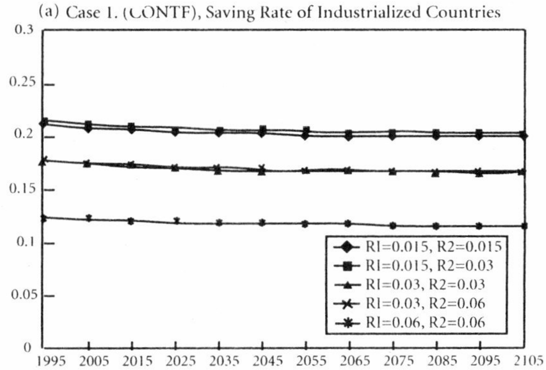
We follow Nordhaus in that, the discount rate (to be precise the pure rate of time preference) for both industrialized and developing countries are 3 percent. However, we examine other cases in which different discount rates apply for different countries and see how this perturbation changes the optimal saving rates and emission control rates in two aggregated regions.

We set $\alpha=1$ throughout the simulations of alternative sets of discount rates. Figures 8 and 9 plot the saving rates and Figures 10 and 11 plot the emission control rates, for both industrialized and developing countries. In each Figure, Panel (a) corresponds to Case 1 (CONTF) while Panel (b) to Case 2 (DIFTF)

From these figures, several observations fol-

Fig. 8

(a) Case 1. (CONTF), Saving Rate of Industrialized Countries



(b) Case 2. (DIFTF), Saving rate of Industrialized Countries

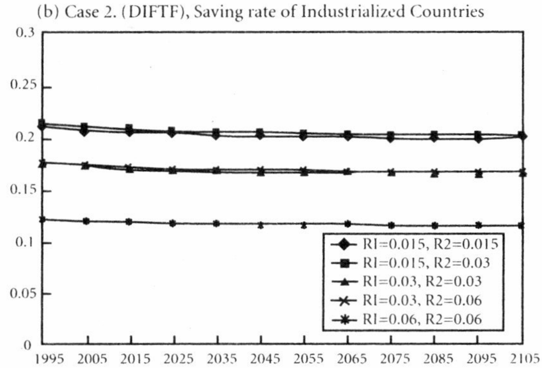
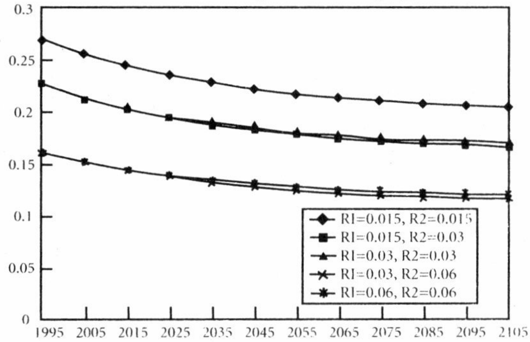


Fig. 9

(a) Case 1. (CONTF), Saving Rate of Developing Countries



(b) Case 2. (DIFTF), Saving rate of Developing Countries

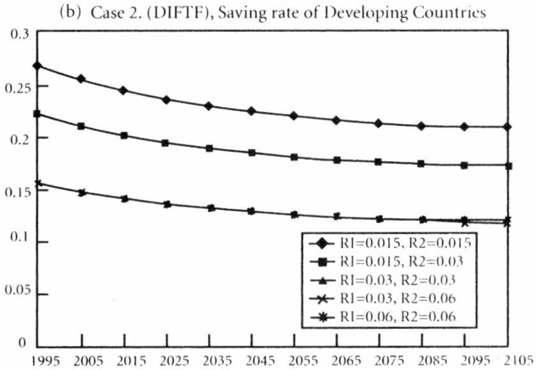
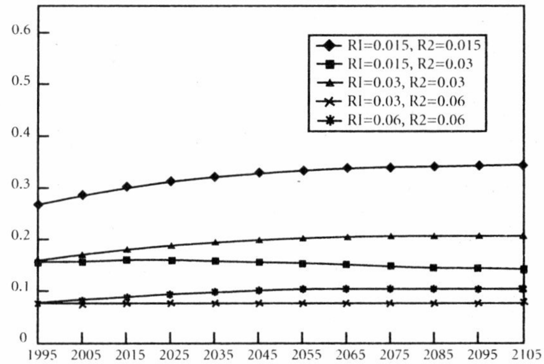
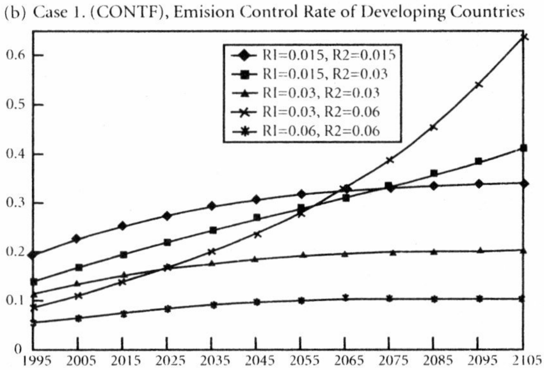


Fig. 10

(a) Case 1. (CONTF), Emision Control Rate of Industrialized Countries



(b) Case 1. (CONTF), Emision Control Rate of Developing Countries



low. First, we can safely summarize that technology differences play no magnifying role on the level of saving rates. Second, the saving rates depend only on home country's discount rates and are insensitive to the level of the discount rates of the counterpart countries. Naturally, home countries' lower discount rates raise saving rates. Third, when the discount rates are the same between two regions, the emission control rates of both regions are stable and their rates get higher as the discount rates get lower. Again it can be said, to the same discount rates, the emission control rates of the developing countries are relatively higher. Fourth, however, when two regions differ in discount rates (to be precise, when the discount rates of industrialized countries are lower than those of the developing countries), the emission control rates of developing countries become rather unstable, leading eventually to very high rates of emission control rates. In this sense, disharmonized shifts in discount rates may cause much larger differences in emission control rates between two regions.

4.3 Size and pattern of side payments

So far, we assumed away side payments. As last simulations, we examine what are the optimal features of side payments for different sets of discount rates. Again, we set $\alpha=1$. We report only the results of Case 2 (DIFTF) as the results of Case 1 (CONTF) did not come somehow out at preliminary computer runs.

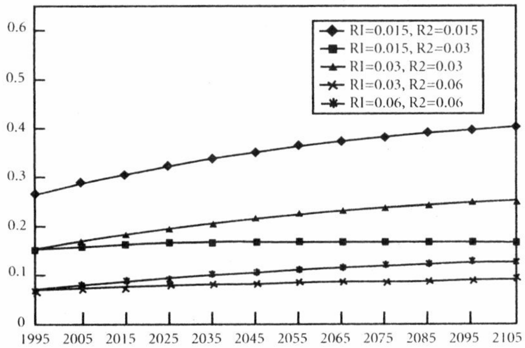
It turns out that, when side payments are effectively transferred, the emission control rates become exactly the same between the industrialized and developing countries. This is because, as we pointed out in Section 2, the functional form and parameters of the emission control effort and damages are the same between two regions. In other words, in terms of the formulation of q^i function of equation (3), not $B_{it}=\mu_{it}E_i$, but μ_{it} alone matters in the DICE model. As plotted in Figure 12, considerably high ratios of transfer payments over production, flowing from the industrialized countries to developing countries, are necessary when the discount rates are the same between two regions. However, when the discount rate of developing countries is higher, the transfer ratios vary significantly and eventually the developing countries become the payer, rather than the receiver, of transfers.

5. Concluding Remarks

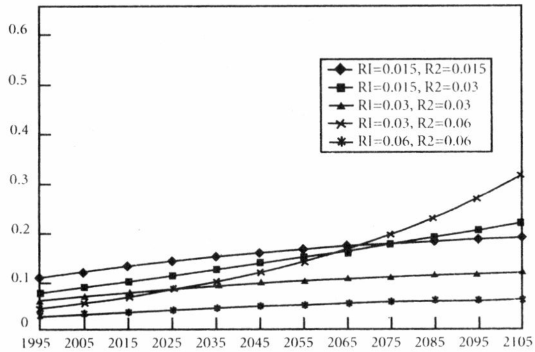
In the present paper, we attempted to evaluate the potential vulnerability of international cooperation to slow global warming. Of course, this kind of skepticism is not new. For instance,

Fig. 11

(a) Case 2. (DIFTF), Emission Control Rate of Industrialized Countries



(b) Case 2. (DIFTF), Emission Control Rate of Developing Countries

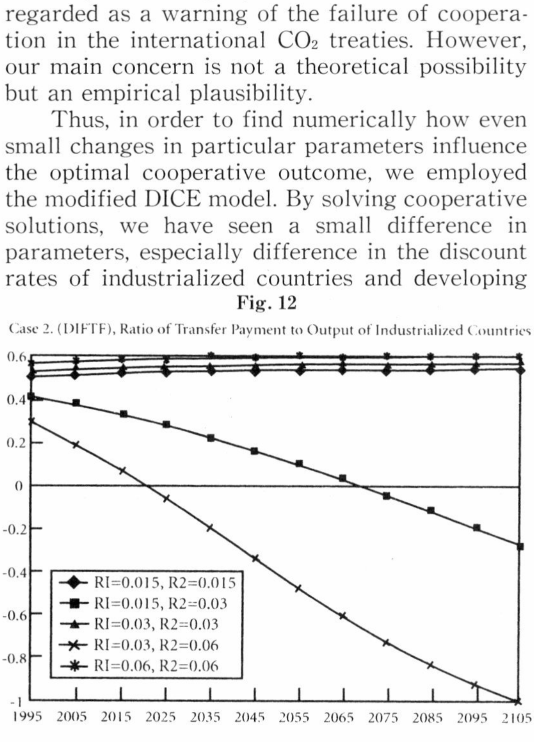


the story of the tragedy of the commons has been regarded as a warning of the failure of cooperation in the international CO_2 treaties. However, our main concern is not a theoretical possibility but an empirical plausibility.

Thus, in order to find numerically how even small changes in particular parameters influence the optimal cooperative outcome, we employed the modified DICE model. By solving cooperative solutions, we have seen a small difference in parameters, especially difference in the discount rates of industrialized countries and developing

Fig. 12

Case 2. (DIFTF), Ratio of Transfer Payment to Output of Industrialized Countries



countries, causes considerable fluctuations in the emission control rates. Also necessary transfer payments between two regions turned out to vary significantly both in size and direction. We have also seen that depending on the potential bargaining power, reduction rates of CO_2 emissions vary considerably.

In the present world, the discount rates (pure rate of time preference) may change depending upon the stages of economic development. If this is really the case, international cooperation may in fact be vulnerable. Also it is unlikely that every country is endowed with equal bargaining power. Rather, bargaining power itself may change depending on the stage of economic development, thus becoming another source of vulnerability of international cooperation.

Although such may be the tentative summary of the present study, we should not become too pessimistic. There are reasons that parameters are not independent each other and, when a certain parameter, say β, shifts in one direction, another parameter, say γ shifts concurrently to offset the negative effect of initial shift in parameter β. Then, we needs to identify such endogeneity of parameter shifts before negating a reliance on international cooperation. This last is the task of future research.

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Notes

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1) Jaeger (1995) briefly summarizes and compares the characteristics of five well known numerical models: Edmonds and Reilly (1985), GREEN by OECD (Burniauz *et al.*, 1991), Jorgenson and Wilcoxen (1992), GLOBAL 2100 by Manne and Richels (1992), and DICE by Nordhaus (1994). As time passes, dynamic optimization has come into the general equilibrium framework of economic growth and climatic changes only to pave in turn the way for dynamic cooperative as well as noncooperative game theories to come in. Recent literature in this field include: Dockner and Long (1993), Hinchy, Hauslow, and Fisher (1994), Kverndokk (1994), and Martin, Patrick and Tolwinski (1993).

2) Not surprisingly, different models have estimated different magnitudes of economic costs of global warming. Although we are aware that the implication of the DICE model has invited certain criticisms from the profession (e.g. Cline (1994)), we would like to appreciate Professor Nordhaus for his openness and permission for anyone to run the DICE model (Nordhaus (1994) p. 191). For recent discussion on the significance of damages, see Jaeger (1995)

and Price (1995).

3) Autonomous emission reduction mostly corresponds to the notion of autonomous energy efficiency improvement (AEEI). The level of AEEI will critically influence future outlook of CO_2 emission. See Burniaux *et al*. (1991).

4) In general, it is not certain whether we could always derive such a well behaved form because externality is involved.

5) As a recent literature on discounting in relation to global warming, see Lind (1995), Manne (1995), Schelling (1995) and Toth (1995), all of which appeared in the recent issue of *Energy Policy*.

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