

## **On Some Integrated Assessment Model Debates**

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## On Some Integrated Assessment Modeling Debates

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### I. Introduction

Integrated assessment modeling has not a long history, but is receiving rapidly growing interest from various disciplines, which has resulted in relatively numerous reviews within a short period (see, e.g., Bruce *et al.* (1996, Chapter 10), Weyant (1994), Rotmans *et al.* (1995), Dowlatabadi (1995), Van der Sluijs (1996), and Kolstad (1996)). Recent activities exhibit enrichment of the assessment from the socio-economic standpoint, on the one hand, and a tendency of putting heavier weight on cost-considerations, on the other hand. This paper attempts to discuss three topics which have been considered unresolved important issues: (1) discounting, (2) technological change in the energy sector, and (3) limiting too-rapid climate change. These topics are all related to the question of optimal timing in limiting global warming. Some authors reviewing the current development in integrated assessment modeling associated with the global warming issue argue that our understanding of the problem does not justify early mitigation measures. The following sections that deal with the above problems in turn, attempt to show that there are balancing arguments to the contrary. Integrated assessment modeling approaches would attain further enrichment if these aspects are more fully integrated into the current models.

### II. Time Discounting

The choice of discount rate in a cost-benefit framework has a long history of debate, and has gained additional fuels in the area of climate change policy discussions. The proposal of "aggressive" abatement policy by William Cline (see Cline (1992)), involving an immediate cutback of global carbon emissions to 40 billion tons annually and subsequent stabilization at this level, seemed to have triggered a heated renewal of the debate, because his conclusion depends crucially upon his choice of a low rate of discount for which he provided a well-documented arguments (Cline (1992), chapter 6).

William Nordhaus, who supports a quite moderate control strategy as optimal (see, e.g., Nordhaus (1990a), (1990b), (1992a), (1992b), (1994), and Nordhaus and Yang (1996)), criticized Cline's approach on various grounds (see, in particular, Nordhaus (1994, chapter 6)), but the most important point is an analytical one; the consistency with a dynamic optimality condition derived from the Ramsey-type optimal growth theory:

$$r^* = \alpha g^* + \rho$$

where  $r^*$  and  $g^*$  are steady-state values of the net marginal product of capital (i.e., the instantaneous real interest rate) and the growth rate of per capita consumption, respectively, and  $\alpha$  and  $\rho$  are elasticity of the marginal social utility of consumption and the pure rate of social time preference, respectively (see Nordhaus (1994, p. 124)). In order for the abatement policy be consistent with the efficiency condition under today's economic conditions, the pure rate of social time preference would be bounded from below by the difference between  $r^*$  and  $\alpha g^*$ . Nordhaus' estimates are:  $r^* = 0.06$ ,  $\alpha = 1$ , and  $g^* = 0.03$ , and hence  $\rho$  is around 3 per cent p.a. rather than 0 per cent assumed by Cline.

In the Proceedings of the 1993 workshop at IIASA (International Institute for Applied Systems Analysis), four papers commented and discussed the Cline approach (Nakicenovic *et al.* (1994)). Perhaps with the exception of Toth (1994), which reviewed the discounting methods adopted in Integrated Assessment Models, three authors appear to support the higher discount rates reflecting market interest rates. For example, Alan Manne (1994) also calls

upon the optimal-growth framework and adopts the steady-state property  $r = \alpha g + \rho$  to derive the social discount rate from the opportunity cost of capital and the rate of growth, assuming  $\alpha = 1$ . He calls this approach descriptive as opposed to prescriptive in order to avoid philosophical debate on the selection of the value of discount rate. At the same time, he criticizes the "prescriptive" approach taken by Cline by showing that if one applies a rate of social discount that is lower than the marginal productivity of capital, then an economy growing along an optimal growth trajectory would be disturbed by a sharp step-up of investment. In other words, to justify the adoption of low discount rate, one needs to give sufficient reasons why we need to make a large jump in both human and physical capital investments in the near future. Schelling (1994) also suggests the use of the market rate of interest "because it tells us something about the opportunity cost of CO<sub>2</sub> abatement."

It is important, however, to note that these arguments are based upon an implicit assumption that the economy under consideration does not suffer from external diseconomies. In the presence of environmental degradation such as global warming, this supposition is not justified (Broome (1992, pp. 90-92)). Private rate of return on capital that does not take into account external social costs underestimates true social productivity of capital. The Ramsey-type optimal growth model must be extended to take into account such externalities, and if the extension is done properly then it is the social rate of return on capital, rather than the private marginal productivity of capital, that must be equal to  $\alpha g + \rho$  in the above formulation. In the presence of environmental degradation, capital is less productive from the social point of view, and hence at the steady-state a lower rate of time discount is consistent with optimal growth. If we apply a higher private rate of return on capital to the economy that is growing along the optimal trajectory, that will dislocate the economy by stepping up near term consumption. Under such conditions the "descriptive" approach must be used with caution not to mislead the social choice.

In order to clarify this point in a more formal manner, let us consider a simple dynamic optimization problem with the following objective function:

$$(1) \quad W = \int U(C, A) e^{-\rho t} dt$$

where  $W$  = social welfare,  $U$  = utility,  $C$  = consumption,  $A$  = atmospheric concentration of greenhouse gases,  $\rho$  = social rate of time preference, and  $t$  = time. Social welfare is defined as a sum of discounted social utility over time. Utility is assumed to depend on global warming as well as consumption. We express partial derivatives by subscripts. Thus, we assume  $U_C (= \partial U / \partial C) > 0$ , and  $U_A (= \partial U / \partial A) < 0$ . This type of formulation has been used fairly widely (see, e.g., Keeler *et al.* (1971), Morton *et al.* (1984), Dasgupta (1995), and Tahvonen and Kuuluvainen (1991)).

Next, we assume that aggregate output ( $Q$ ) is produced by the production function:

$$(2) \quad Q = F(K, A)$$

where  $F$  = production function, and  $K$  = capital stock. Labor supply and the level of technology are assumed constant for simplicity of exposition. Here, we assume that  $F_K > 0$  and  $F_A < 0$ . In other words, global warming tends to reduce the total factor productivity. This formulation is also used extensively in the literature of environmental economics. (See, e.g., literature cited above and Klaassen and Opschoor (1991).)

The level of emission of greenhouse gases ( $E$ ) is assumed to be positively related to output and negatively related to abatement expenditure ( $M$ ):

$$(3) \quad E = E(Q, M)$$

where  $E_Q > 0$  and  $E_M < 0$ . Aggregate output is devoted to consumption, investment, and abatement activities:

$$(4) \quad Q = C + I + M.$$

Thus, in the above formulation, environmental externalities are represented in two forms: dis-amenity in consumption and loss of output in production. The former is evaluated directly as a loss of social utility, while the latter loss is registered in terms of commodities. Falk and Mendelsohn (1993) distinguished damage costs and abatement costs, and considered an optimal strategy to minimize the sum of these costs. In the above approach, the

abatement costs are represented by  $M$ .

Finally, the dynamics of capital and atmospheric stocks are given by

$$(5) \quad \dot{K} = I - \delta K$$

$$(6) \quad \dot{A} = E - \omega A$$

where  $\delta$  and  $\omega$  are relevant depreciation parameters.

The above system can be summarized as

$$(7) \quad C = F(K, A) - I - M$$

$$(8) \quad \dot{K} = I - \lambda K$$

$$(9) \quad \dot{A} = E(F(K, A), M) - \omega A,$$

and the current Hamiltonian is given by

$$(10) \quad H(I, M, K, A; \mu, \omega) = U(F(K, A) - I - M, A) + \mu[I - \delta K] + \lambda[E(F(K, A), M) - \omega A]$$

where  $\mu$  and  $\lambda$  are shadow prices of capital stock and environmental degradation stock, respectively.

The first order conditions for optimum are:

$$(11) \quad \mu = U_C \quad [\text{as } H_I = 0 \text{ implying } -U_C + \mu = 0]$$

$$(12) \quad \lambda = U_C / E_M \quad [\text{as } H_M = 0 \text{ implying } -U_C + \lambda E_M = 0]$$

$$(13) \quad \dot{\mu} - \rho \mu = -H_K = -[U_C F_K - \mu \delta + \lambda E_Q F_K]$$

$$(14) \quad \dot{\lambda} - \rho \lambda = -H_A = -[U_C F_A + U_A + E_Q F_A - \lambda \omega].$$

The dynamics of shadow prices can be summarized as

$$(15) \quad \dot{\mu} / \mu - (\rho + \delta) = -F_K [1 + E_Q / E_M]$$

$$(16) \quad \dot{\lambda} / \lambda - (\rho + \omega) = -E_M [F_A (1 + E_Q / E_M) + U_A / U_C].$$

For the moment, let us assume that  $E_Q = 0$  in equation (15). That is, external effects are assumed away and the economy is in a first-best situation. Then, equation (15) is simplified into

$$(17) \quad \dot{\mu} / \mu - (\rho + \delta) = -F_K$$

Let us also assume, for the moment, that utility depends only on consumption. Then, from equation (11) we obtain

$$(18) \quad \dot{\mu} / \mu = -\eta g$$

where  $\eta (= -U_{CC} / U_C C)$  is the absolute value of the elasticity of marginal utility of consumption with respect to the level of consumption and  $g (= \dot{C} / C)$  is the rate of growth of consumption. Under these assumptions, we can obtain a familiar result:

$$(19) \quad \rho + \eta g = F_K - \delta.$$

This is a much advocated "correct way" of obtaining the level of social rate of time discount that is consistent with the market interest rate. We should note, however, that Cline (1992) and Fankhauser (1995) only considered the left-hand side of the equation.

In a world of negative externalities, however, equation (15) has additional elements to be taken into account. Nordhaus (1994) and other literature fail to pay due attention to this

aspect even though they are discussing global negative externalities. Combining equations (15) and (18), we obtain

$$(20) \quad \rho + \eta g = FK[1 + EQ/EM] - \delta.$$

Since  $EQ/EM < 0$ , the right-hand side is less than the market rate of interest, or the private marginal productivity of capital ( $FK - \delta$ ). The term  $FK[1 + EQ/EM]$  is the (gross) social marginal productivity of capital, and it is this rate (net of depreciation) that becomes equated with the consumption rate of discount at the steady-state along the optimal trajectory. This is one reason why Broome (1992) argued against using the producer interest rate for the purpose of discounting, because the production of commodities involves GHG emissions and other environmental damages and these negative externalities are not included in the producer interest rate. It does not represent the true opportunity cost of postponing commodities. (See also Toth (1994), p. 489.)

Instead of equation (3), Weitzman (1994) used a specific functional form:

$$(21) \quad E/Q = G(M/Q)$$

to consider the effects of abatement costs. Since  $E = Q \cdot G(M/Q)$ , we have

$$(22) \quad EM = G'$$

and

$$(23) \quad E_Q = G - G'(M/Q) = G(1 + \varepsilon)$$

where  $\varepsilon = -(G'/G)(M/Q)$  represents the absolute value of the elasticity of emission/output ratio with respect to abatement intensity (i.e., the ratio of abatement expenditure to output). Therefore, we obtain

$$(24) \quad E_Q/EM = -(M/Q)(1 + 1/\varepsilon).$$

As Weitzman defines  $\gamma$  as  $-EQ/EM$ , we can rewrite equation (15) as

$$(25) \quad \rho + \eta g - \dot{\mu}/\mu = FK(1 - \gamma) - \delta.$$

This is essentially what Weitzman (1994) derived in a different fashion. Since  $\gamma$  represents the amount of expenditure required to abate pollutants emitted by adding one unit of output, private marginal productivity of capital must be adjusted by multiplying  $(1 - \gamma)$ . Equation (25) is also implicit in Keeler *et al.* (1971) because their first model is almost identical to ours.

In view of the fact that  $\gamma = (M/Q)(1 + 1/\varepsilon)$  under the abatement function (20), Weitzman (1994) attempted to make a rough estimate of  $\gamma$ . If we follow Weitzman in assuming that  $\varepsilon$  lies between 0.5 and unity, then,  $\gamma$  would lie between 0.10 and 0.15 if the long-run share of abatement expenditure in GDP is 5%, or between 0.06 and 0.09 if the latter share is 3%. Under these circumstances, Nordhaus' estimates of 16% gross rate of return on capital with the depreciation rate of 10%, unitary elasticity of marginal utility of consumption ( $\eta$ ), and 3% p.a. rate of growth of consumption, would lead to the range of utility discount rate of 0.6-1.4% p.a. or 1.6-2.0% p.a. Nordhaus' estimates imply 6% market interest rate, but if the market rate is set at 5% as in Manne and Richels (1995), then the utility discount rate would become still lower.

I should like to emphasize one additional point which receives scant attention in the discounting debate. It is the behavior of the shadow price  $\mu$  along non-steady-state trajectories. Since  $\mu = UC = UC(C, A)$ , we can write

$$(26) \quad \dot{\mu}/\mu = -\eta g - \alpha \dot{A}/A$$

where  $\alpha (= -(U_{CA}/U_C)A)$  is the absolute value of the elasticity of marginal utility of consumption with respect to the environmental stock. (Here, we assume that increasing environmental pollution stock tends to reduce the marginal utility of consumption. See Keeler *et al.* (1971)). Thus, equation (25) now becomes

$$(27) \quad \rho + \eta g + \alpha \dot{A}/A = FK(1 - \gamma) - \delta.$$

That is, when the environmental degradation is still going on, then, in addition to

consumption discounting due to rising level of consumption, further consumption discounting is required because of declining consumption utility due to environmental degradation. In other words, the wedge between the (social) opportunity cost of capital and the pure rate of time discount can become larger than in the steady-state. In passing, Falk and Mendelsohn (1993) emphasized the importance of dynamics of the trajectory for various reasons. Their optimality condition, concerning the efficient strategy for greenhouse gases, involves marginal changes in the value of objective function arising from changes in the pollution stock, just like our term  $\alpha \dot{A}/A$ .

The above discussions all relate to the ways how we model the global warming rather than to stating some philosophical positions. Some of the existing gaps in the discounting debate is hoped to be narrowed down by making relevant assumptions more explicit.

### III. Technical Change

The evolution of new energy technology has an important bearing upon the cost-efficient pathways of carbon abatement control policies. It is easy to see that the possibility of introduction or deployment of carbon-free energy technology in a certain future time will shift the cost-effective pathway of carbon abatement toward later periods. In other words, the assumption concerning the exogenously given pattern of technological evolution can have a strong influence upon the optimal or cost-effective pathways of mitigation policies. In many integrated assessment models of climate change, technological evolution in the energy sector is assumed exogenous to the model, and the pattern of calculated optimal abatement policy hinges upon this assumption.

Three years ago, when the IPCC Working Group III Workshop was held at Tsukuba, Japan (IPCC (1994)), Richels and Edmonds (1994) made an early contribution to the choice of optimal timing in abatement strategy. The rapporteur neatly summarized their principal findings:

Shifting emission reductions to the future significantly reduces control costs because of discounting and the availability of lower cost less carbon-based technologies in the future. ... Rather than choosing arbitrary emission paths, more attention needs to be devoted to identifying those paths that minimise the costs of achieving a particular target such as stabilisation of atmospheric concentrations of greenhouse gases. Gains from waiting include the opportunity to develop new cost effective energy technologies. IPCC (1994, p. 87.)

Similar assertion can be found in more recent literature (e.g., Manne and Richels (1995), Richels and Edmonds (1994), and Wigley, Richels and Edmonds (1996)). However, such factors as lower discount rates, inclusion of secondary benefits (which occur in the nearer future), and heavier regional damages expected in the distant future in lower income countries, would make earlier responses more appropriate (see my comment summarized by the rapporteur in IPCC (1994, p. 88)). Integrated Assessment Models so far do not seem to have paid sufficient attention to these issues (Toth (1995, pp. 262-3) and Kolstad (1996, p. 16)).

In addition to the factors mentioned above, the assumption of exogeneity of new energy technologies or of efficiency improvements is too important to be left without further elaboration. Innovation is much influenced by economic and other institutional factors including environmental policy measures. For a recent review of theory and empirical evidence, see Kemp (1997). Studies tackling the problem of clarifying the role of technical change in shaping the future Green house Gas (GHG) emission paths have been emerging (see, e.g., Grubb *et al.* (1994), (1995), Hourcade and Chapuis (1994), (1995), and Goulder and Schneider (1996)). Furthermore, at least one integrated assessment model of climate change explicitly attempted to endogenize technology learning process in the energy sector, and reached a conclusion, "The message from this experiment is that early decisions for the introduction of new technologies are essential in reaching good economic performance over

time.” This means that cumulative investments are reduced considerably and that the overall discounted costs of the energy system is reduced substantially (Messner (1995, p. 16.)).

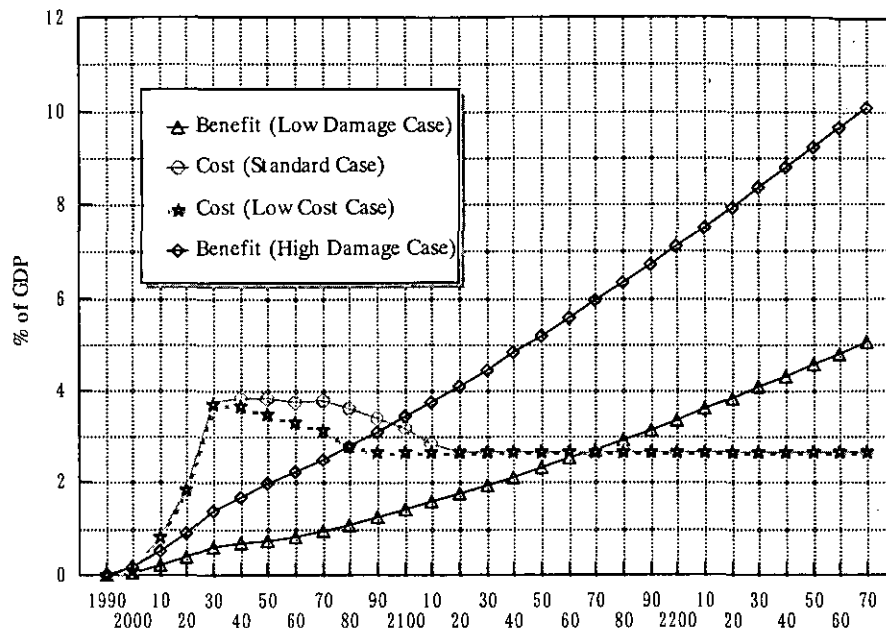


Figure 1: Cline's Cost-Benefit Analysis of Global Warming

In order to understand the implication of changing assumptions concerning technological factors affecting carbon reduction, I first used William Cline's cost-benefit model in Cline (1992). Figure 1 contains three lines that represent Cline's original scenarios and one additional line (with diamond-marks). Two benefit curves are sloping upward gradually and persistently. On the other hand, cost curves rise quite sharply in the near term (after "no-regret" opportunities are exhausted), then gradually decline as new technologies become available, and stabilize afterwards. The cost curve for Low Cost Case is the one that is added, which was obtained by changing the trend coefficient of the carbon reduction cost function in the Cline model. (That is, increasing the  $\beta$ -coefficient in absolute value in Equation (7.14a) by one standard error - cf. Equation (5.3)- in Cline (1992). This adjustment makes the carbon abatement costs decline more rapidly after 2030.) As Cline noted, net benefit of mitigation is negative near-term and positive in the far-end. The cost-benefit framework thus clearly shows that lowering the costs of mitigation can make aggressive response more attractive.

Perhaps, a more relevant simulation exercise would be to somehow endogenize technological evolution. I have made an attempt toward this direction by using the MERGE model. This model is an optimization model with fairly detailed energy sectors (for the MERGE model, see, e.g., Manne, Mendelsohn, and Richels (1993)). The original MERGE model contains some new energy technologies both in electric and non-electric sectors. In the present exercise, two electricity generation technologies and one non-electricity energy technology have been subject to modifications. In the electricity sector, ADV-HC (advanced high-cost carbon free) and ADV-LC (advanced low-cost carbon free) technologies are assumed to be potentially introduced as early as 2010 and 2020, respectively, with estimated costs of 75.0 and 50.0 mills/kWh in terms of 1990 US dollars. In the non-electricity sector, NE-BAK (non-electric backstop, carbon free) technology is assumed to be available at the cost of 13.33 US dollars (1990) per GJ of crude oil equivalent. We modified the program so that these new energy costs can be reduced by cumulated R&D expenditure as follows:

(28). (energy cost (t))<sub>i</sub>

$$= (\text{exogenous energy cost (t)})_i \cdot \exp[-\eta_i \cdot (\text{cumulated R\&D investment (t)})_i]$$

where  $i$  denotes energy technology index, and  $\eta_i$  the elasticity of energy costs with respect to cumulated R&D investment, and  $t$  the time period. Since our purpose is to see how optimal abatement patterns are qualitatively affected by this partial endogenization of technical change, the values of the elasticity  $\eta_i$  are determined by trial and errors so that feasible solutions are generated.

R&D investment is introduced only in USA and the OOECD (other OECD) region. The simple average of resulting energy costs (in each technology) in the two regions is then applied to all regions, including the first two. R&D expenditure in the developed regions thus play a role of public goods. Realistically, we must consider the burden-sharing of developmental costs, but this question is ignored for simplicity's sake. The original assumption of availability of new technologies at no cost shares the same problem. The only novelty here lies in the fact that the level and timing of potential adoption of advanced energy technologies are affected by current consumption-investment decisions.

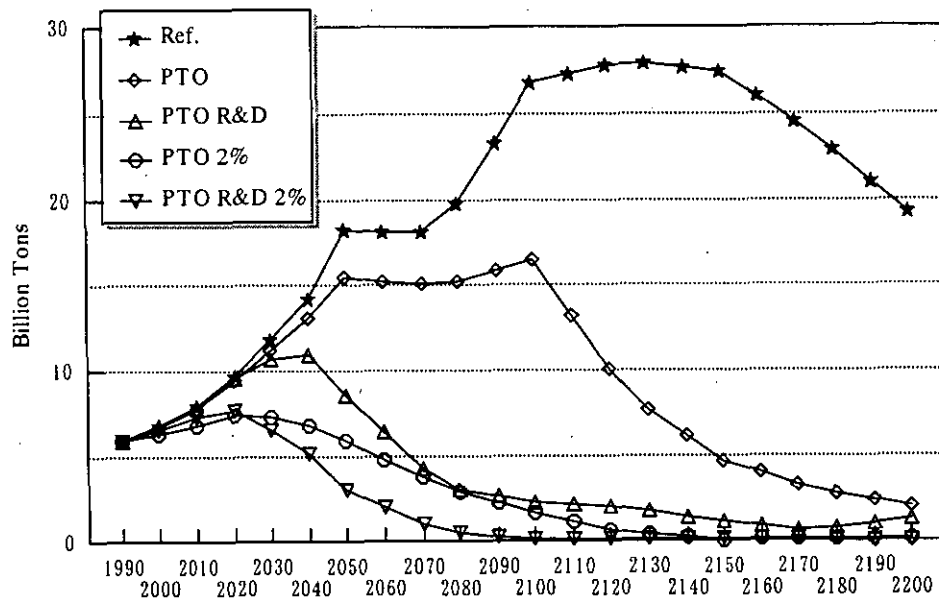


Figure 2: Total Carbon Emissions

Ref. = References Scenario

PTO = Pareto Optimal Scenario

PTO R & D = PTO Scenario and R & D in Energy Sectors

PTO 2% = PTO Scenario with 2% Rate of Return

PTO R & D 2% = PTO Scenario and R & D in Energy Sector with 2% Rate of Return

Figure 2 presents global carbon emissions for five scenarios of which first two are taken from original scenarios (Manne and Richels (1995)). Reference Scenario is the 'business as usual case', and global CO<sub>2</sub> emissions tend to grow until they peak out around 28 billion tons carbon in the 22nd century. PTO Scenario is the "Pareto Optimality Scenario" in which the



international community agrees upon a policy of balancing costs of abatement against the damages of global climate change. It involves an interesting scheme of international emission-permits allocation, but I shall not dwell on this topic here.

The third scenario, PTO and R&D Scenario, introduces the R&D scheme explained above into the PTO Scenario. As expected, global emission reduction starts much earlier than in the PTO Scenario. Research and development investment that reduces the costs of future energy technologies affects the current consumption-savings decision. A reduction in current consumption can raise future consumption not through a future increase in production capacity but through reduced throughput in the future. Therefore, both productive and R&D investments play a similar role in the over-time consumption decisions. A major difference is that while capacity investment tends to aggravate future environmental degradation, R&D investment in the cleaner energy technology has an exactly opposite property.

As I noted earlier, the responses of future energy costs to R&D expenditure in the above simulation experiments have been generated by parameters given rather arbitrarily. Therefore, we can draw only qualitative observations, and an apparent large gap between the lines in Figure 2 should not be taken too seriously. However, it remains true that future technological opportunities are largely a matter of over-time decision making, and the assertion that the availability of future clean technologies tends to delay the optimal timing of abatement must be re-examined in this framework. Our analysis shows not only that technology development plays an important role in the mitigation strategy, but also that it should go hand in hand with near-term abatement measures rather than "as an alternative to" them.

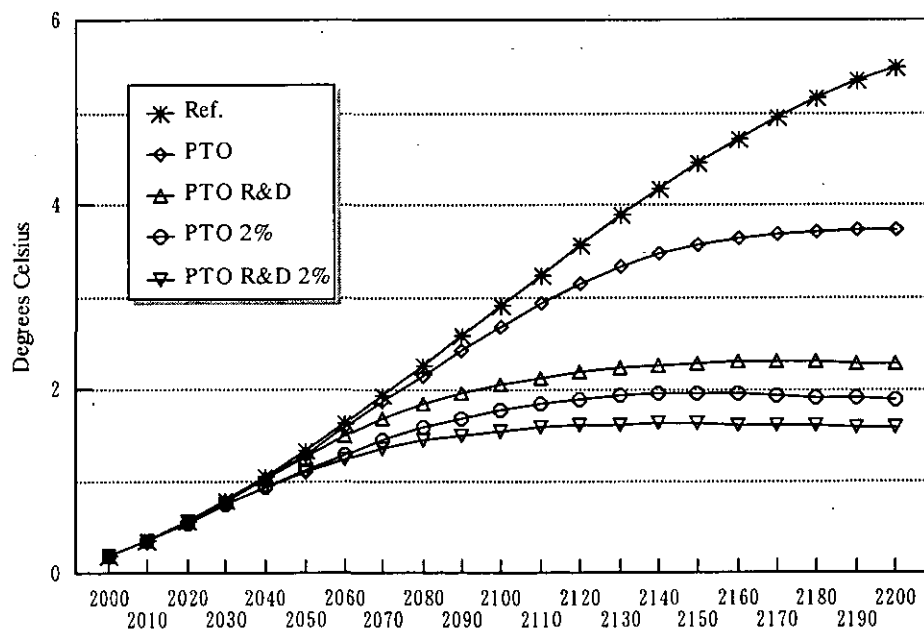


Figure 3: Actual Temperature Increase

The bottom two lines in Figure 2 represents two scenarios when the real rate of return on capital (which is given exogenous in the MERGE model) is reduced from the default 5% value to 2% (per annum). In the MERGE model, the utility discount rate is determined as the difference between real rate of return on capital and the rate of growth of the economy at

large (see the previous discussion of Professor Manne). Therefore, this exercise actually implies a reduction of utility discount rate by 3 per cent annually. As the results clearly indicate, the shape of optimal abatement pathways are quite sensitive to the choice of discount rates. Figure 3 presents the results for actual temperature increases for each scenario.

#### IV. Speed Limit

Those who emphasize the importance of economic considerations in recent debate on the timing of GHG emissions abatement strategies tend to focus attention on the over-time allocation of a certain carbon emission budget (see, e.g., Wigley *et al.* (1996)). The cost-minimization criterion then favors a pathway that allows relatively generous control in the near term and a sharp cut in the later years; that is, a boom-bust style emission pathway rather than a less wild emission profile. Although there are some integrated assessment models that have been used to support such emission strategies, there are still other integrated assessment models incorporating additional considerations to which the former group does not pay due attention: that is, the speed limit of global warming (see, e.g., Alcamo and Kreileman (1996) and Matsuoka *et al.* (1996)). These latter models typically consider several climate targets such as (a) changes in global average surface temperature over an extended time period, (b) rate of temperature change per decade, (c) changes in global average sea level; and it is found that the second of these climate targets is often violated by various emissions scenarios.

The speed limit for a decadal rate of temperature change is required to protect ecosystems and bio-diversity, especially tree and coral species. Heil and Hootsmans (1990, p. 70), for instance, conclude:

In order to prevent irreversible disturbances to natural ecosystems and to maintain biodiversity, targets should be based on the adaptive capacity of ecosystems in regional climate and climate-related processes ... vegetation responses to climatic change indicate that migration of tree species especially is limited to average rates of approximately 50 km per century, which corresponds to a temperature change of 0.5°C by 2100 ...

It is apparent that temperature change should be as gradual as possible to reduce the inability of species to respond to temperature change. It can be concluded from the literature that a rate of temperature change less than 0.1°C per decade may be tolerable ...

(see, also, Jaeger (1988), Rijsberman, Heil, and Bower (1990), Sassin (1990), and Gleick and Sassin (1990)). Although more scientific knowledge about ecosystem capabilities and more information about the magnitude of potential loss of bio-diversity are wanting, it seems clear enough that not only the ultimate stabilization level of atmospheric concentration but also the interim pathway is important in formulating climate change policies.

Alcamo and Kreileman (1996) found that conceivable emission profiles, such as those prepared by IPCC, tend to violate different climate goals at different times so that several goals should be taken into account when an emission profile is evaluated. In their evaluation of IPCC scenarios, the rate of temperature change became the limiting climate indicator in the earlier part of the simulation period. This gives a warning to an approach that supports a relatively lax abatement in the near term with a steep cut in later periods.

This result is confirmed by Matsuoka *et al.* (1996). Both models also suggest that Annex I countries must continue to follow tight reduction pathways as long as non-Annex I countries do not join in the emission stabilization/reduction group.

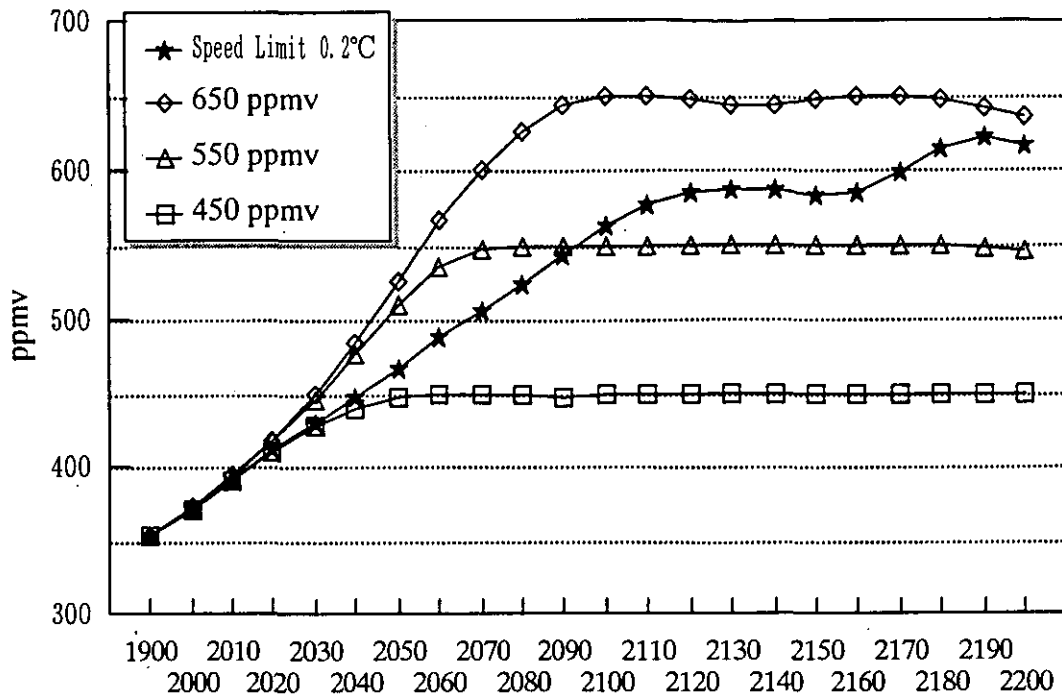


Figure 4 : Limiting the Rate of Decadal Temperature Increase

Figure 4 illustrates the effect of imposing a speed limit to the solutions of the optimizing model, again using the MERGE model. Three lines corresponding to the stabilization levels of atmospheric concentration (450, 550, and 650 ppmv, respectively) are those given in the original model. The line with asterisk marks is obtained by constraining the maximum rate of increase in actual temperature per decade to  $0.2^{\circ}\text{C}$  in the "Pareto Optimal" solution mentioned above. It can be seen that only the concentration profile for 450 ppmv level is consistent with the speed limit. The concentration profile that does not violate the short-run speed limit of  $0.2^{\circ}\text{C}$  temperature increase lies between 450-line and 550-line up to the year 2100. If, therefore, the adaptation capabilities of ecosystems with respect to the speed of temperature increase are binding, then such information should be incorporated in the cost-benefit framework by making the value of the damage function dependent upon not only the level of the average surface temperature but also its rate of change. Scientific research in this field would be requisite before we can properly evaluate the optimal timing issue.

## V. Summary and Conclusions

In this paper we examined three questions that often come up in the integrated assessment debates. It is often the case that the choice of the level of discount rate is ultimately alleged to the differences in philosophical positions. Our discussion in Section II shows that there still remain enough room to resolve the problem if implicit assumptions in modeling are made more explicit.

In economics we distinguish efficiency and equity, and the question of time discounting is often discussed under the heading of intergenerational equity. When discounting is applied to planning problems that involve negative externalities over time, however, the discounting

method that uses market interest rates implies inefficiencies viewed from the society as a whole. We should be concerned with social efficiency rather than market efficiency in such a situation.

Moreover, when environmental stock degradation adversely affects the marginal utility of consumption, then usual discussion concerning consumption discounting must also be modified. In so far as the stock of environmental resources is declining over time, or as the pollution stock is increasing over time, then changes in marginal utility of consumption due to negative consumption externalities must be compensated in the discounting process just as they ought to be when the level of consumption is changing over time.

If these two problems are handled properly, much of the current gap in the discounting debates would be narrowed down, because they are no philosophical problems but simply differences in assumptions.

Section III gives a rough and ready way of showing the importance of the role of endogenous energy technology development in the discussions of global warming. The assumption that advanced, cleaner energy-technology is given at certain time period in the future like manna from the heaven will certainly induce rational agents to postpone costly abatement measures to combat global warming. By just changing this assumption a little, we can make the technology development dependent upon the current consumption-investment decisions, and the prospects of long-term gains may stimulate current investment in R&D in the energy sector, implying that earlier actions than otherwise would become optimal. It should be noted, however, that this scenario is dependent upon another assumption: that investments in R&D having the property of public goods will be pursued optimally from the social point of view.

Finally, the problem discussed in Section IV draws our interest to the question which has so far received relatively little attention. More scientific information, as well as information concerning the evaluation of resulting damages, is essential.

In concluding the paper, I should like to emphasize the fact that by making the model programs open for access to interested researchers, the role of implicit/explicit assumptions in the original formulation could be assessed more clearly and objectively. Robustness and sensitivity of the results could then be more easily and widely recognized, and further research could be facilitated. The DICE and MERGE models are excellent examples in this respect. Although larger models might involve technical problems to be overcome, efforts of producing mini-versions for communication purposes will be rewarding. In this way, we shall be able to invite researchers from wider areas. At the moment, integration of sectoral policies such as transportation, agricultural, and urban planning policies are not satisfactory. However, integration of economy and the environment should be much easier in terms of modeling than what Brundtland Commission aimed at ten years ago.

## ACKNOWLEDGMENT

The author is grateful to Tsuneyuki Morita, Shunsuke Mori, and Kenji Yamaji for helpful comments on an earlier draft.

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