

DYNAMIC SIMULATION OF GLOBAL ENERGY MACRO ECONOMIC MODEL BY INTRODUCING DAMAGE COSTS INTO ACCOUNT SYSTEM

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Abstract

In this paper, the authors analyze the global consumption level influenced by magnitudes of damage costs in the scenario where those are paid or not by regional economic sectors, by using dynamic optimization technique. The environmentally sustainable income (net income), which is derived by subtracting the monetary costs of depletion of non-renewable resources and damage costs from the traditional national income, is introduced in the model. Six scenarios which have different damage costs per unit volume of pollutant with/without afforestation program are assumed, and then the carbon emission, net consumption and gross consumption are calculated in the optimization throughout the 21st century. The scenarios, in which damage costs are counted in the global economic welfare, have more reduced emission of pollutants and less consumption of natural resources than in the reference scenario with the conventional account system. The sum of the discounted net incomes introduced in the environmental account system is more than the one in the conventional account system. Furthermore, by afforestation program in the environmental account system, more consumption and more carbon reduction are obtained than without afforestation program.

KEYWORDS: *Sustainability, Account System, Damage Cost, Dynamic Optimization Model*

1. Introduction

As countermeasures to the global warming issues, various analysis, evaluations and policy orientations have been proposed by the Intergovernmental Panel on Climate Change (IPCC). The application of economic tools which do not depend on direct regulation has gained much attention as one of the socio-economic tools mitigating global warming effects. The expected plus or minus economic incentives to the economic sectors would result in indirect control of greenhouse gases, especially carbon dioxide (CO₂). Economic tools consist of taxes and charges, marketable permits, deposit-refund systems and financial assistance. Undesirable material balance does not yet evaluate through the market in the global scale. This means that the measure of internalizing the environment in economic welfare is not reflected in the economic index, such as Gross Domestic Product (GDP), which has very large influencing power on socio-political decision making.

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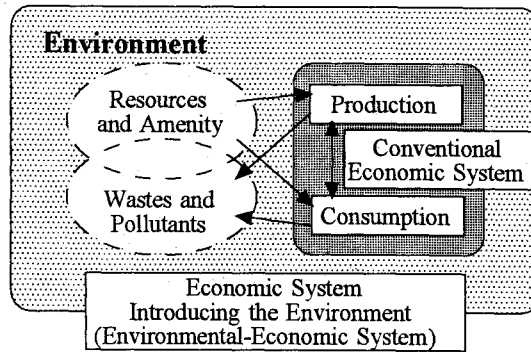


Figure 1. General Concept of New Environmental-Economic System Including Conventional Economic System

Various economic models have been developed and applied to policy analysis in the world. Recently, models which integrate the environment and the economy have appeared such as DICE (Nordhaus, 1994), CETA (Peck and Teisberg, 1992), MERGE (Manne and Richels, 1995), and so on. For example, DICE shows reduction of production amount induced by global warming.

The joint interactive system of environmental economy in this paper is shown conceptually in Fig. 1, which indicates the relationship between economic activities and the environmental burdens/services in this system by using a new proposed model. Human welfare represented by the expanded economic system such as the SEEA (Satellite System for Integrated Environmental and Economic Accounting) is considered in a dynamic model and analyzed from the viewpoint of intergenerational sustainability. This study is a prospective research being different from the retrospective research by Repetto et al. (1989), which showed the economic growth in Indonesia accompanied by severe depletion of natural resources.

In chapter 2, the authors review the concepts of environmental values which occupy an important position in the expanded environmental-economic system. A new modified aggregated index in the environmental-economic system is proposed, which has significant roles in reflecting the account system to the dynamic optimization model. In chapter 3, the authors identify and evaluate economic repercussions of changes in environmental goods and resources into the model. To construct the model, the authors simply follow the skeleton and optimization technique of "Global 2100" by Alan S. Manne and Richard G. Richels (1992). Now, "Global 2100" has been developed to MERGE model by Manne and Richels (1995). This MERGE model includes market and non market based damages by global warming, which is evaluated in production process and utility process, respectively. Whereas the authors modify "Global 2100" to evaluate the environmental damages which come to be taken into consideration for both the market based damages and non market based damages in the account system. In chapter 4, the output of the simulations and above mentioned considerations are looked into. In the last chapter, the conclusion of this paper is described.

Energy related linkage of observed pollutants and resource depletion are discussed in world model modified Global 2100. Money flow such as in disposal of waste and sewage are not accounted, because "Global 2100" does not express these services separately but aggregates in unit production function. Thus, all the environmental burdens are regarded as negative goods. In this paper the issues beyond the year of 2100 is not of concern.

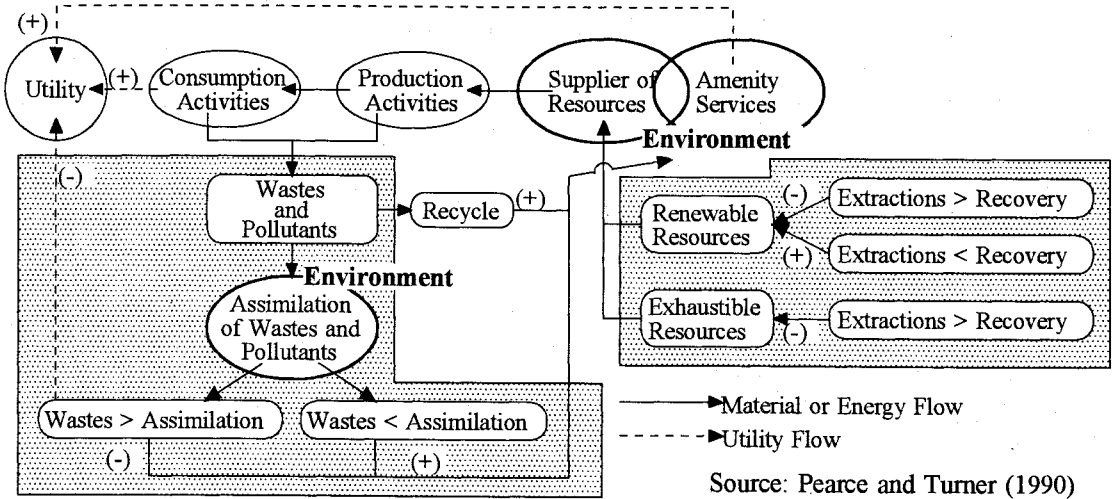


Figure 2. Environment and Economic Activities

2. Introducing Economic Indices Pertinent to Environmental Assets

2.1 Environmental Resources for Sustainable Society

“Sustainability” is one of the most important keywords to evaluate the global warming issues. This word has been used worldwide, since World Commission on Environment and Development (WCED) proposed that “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). Regarding the various implications of sustainable society, Morita et al. (1992) grouped these interpretations into three categories of key concepts of sustainability; stable metabolism natural environment, intergenerational equity, and social justice of welfare allocation. In this paper, sustainable society is defined to be the society in which monetarily evaluated environmental depletion are reflected in decision making economic policy orientations.

The present national accounting system, SNA (System of National Accounts) is said to be one of the most significant social inventions of the 20th century (Repetto et al., 1989). The economic index, GDP, calculated in this system, has a role of giving large economic and political impacts to nation-level policy-making in both developed and developing countries. However, this index has also various shortcomings. It expresses only market-based repercussions of economic activities, and ignores changes of quality and quantity of environmental resources on which various economic activities depend.

In order to audit above mentioned negative impacts of economic activities, the Hicksian income is introduced instead of the conventional income. Hicks (1970) defined income as “a man’s income as the maximum value which he can consume during a week, and still expect to be as well off at the end of week as he was at the beginning.” From the viewpoint of the Hicksian income, the depletion of environmental resources as in petroleum extraction and in air pollution should be subtracted from the national income, in the same manner depreciation of

fixed capital in private firms. To assess the Hicksian income, the authors evaluate the shaded factors in Fig.2, which is illustrated by Pearce and Turner (1990).

2.2 Introducing Environment Conscious Frame of National Economy

The GDP index in SNA simply implies the market scale, however does not include non-market repercussions in the wide concept of social welfare. Therefore many proposals of advanced economic account system have been carried out since 1970s (El Serafy and Lutz, 1989). The first formulation is MEW (Measure of Economic Welfare) proposed by Nordhaus and Torbin (1970). In Japan, NNW (Net National Welfare) was put into practice by the Economic Planning Agency (Economic Council, 1973). Besides those, the United Nations (1992) has revised SNA, it is called System for Integrated Environmental and Economic Accounting (SEEA). In SEEA, the environmental performance such as prevention and restoration activities, degradation of environmental quality, depletion of resources, environmental services and so on are tabulated along with production and consumption activities in the account matrix.

Based on past experiences, the authors develop a new concept of the sustainable income in integrated environment and economy model, "Global 2100." The sustainable income in this research is measured in terms of Environmentally Sustainable Product (ESP) as follows;

$$\begin{aligned}
 & \textit{Environmentally Sustainable Product (ESP)} \\
 = & \textit{Gross Domestic Product} \\
 - & \textit{monetary costs of depletion of natural resources} \\
 - & \textit{abatement costs of pollutants} \\
 - & \textit{maintenance costs to conserve environment} \\
 - & \textit{damage costs due to environmental pollution.} \tag{1}
 \end{aligned}$$

"*Monetary costs of depletion of natural resources*" are generally regarded as costs for compensating the loss of natural resources for future generations' use. "*Abatement costs of pollutants*" have been recognized as costs of discharge control for pollution prevention. "*Maintenance costs to conserve environment*" are considered to be costs for keeping the environmental resources sound for the future generations. "*Damage costs due to environmental pollution*" are regarded as costs for compensating the damaged environment or injured persons.

The improved economic indices, including ESP, are able to express the significant damage in environmental assets, but they have not been widely used. Even if the amount of GDP is modified in terms of imputed values of environmental damage, the original role of GDP which indicates the scale of market activities still fails. Without actual aggregation of negative monetary impacts, these extended indices are liable to fall into auxiliary in the conventional national income system. Therefore in the first epoch, monetary flow intrinsically associated with compensation of damaged environment is configured as counter flows to such as making use of environmental resources and so on in Fig.3.

2.3 Valuation of Environmental Resources

In order to calculate ESP, it is necessary to evaluate environmental resources in monetary terms. Valuation techniques of environmental goods and assets are grouped into the three as follows;

1) valuation based on the observed market prices

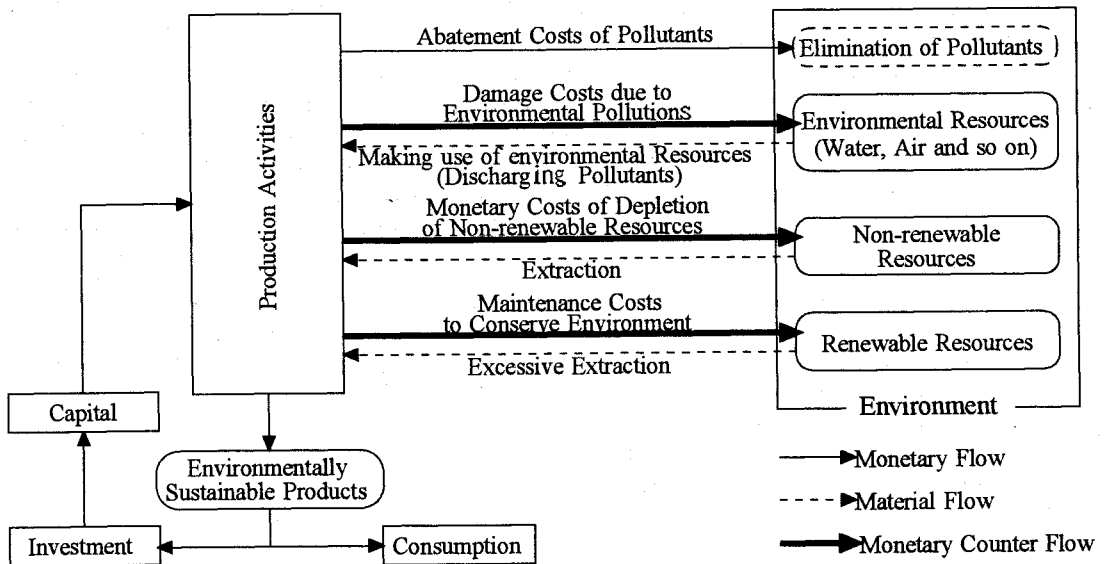


Figure 3. Concept of Sustainable Society Including the Environment

- 2) valuation based on the replacement costs
- 3) valuation in the contingent market.

As environmental goods and resources are not sold or bought in any market, they are evaluated by means of the method 2) or 3). Valuation of the third method is based on the willingness to pay (WTP) using a questionnaire. In this method, WTP includes the consumer surplus. But the account system does not have a separate column for consumer surplus. This means that WTP must not be directly linked to the account system. Therefore, in this paper, the environmental resources are evaluated on the method 2), and monetary flow as counter and material flow are in bilateral relationship assumed in Fig.3. Then Both of them become in balanced.

3. Building the Global Model for Sustainable Society

3.1 Global Model "Global 2100"

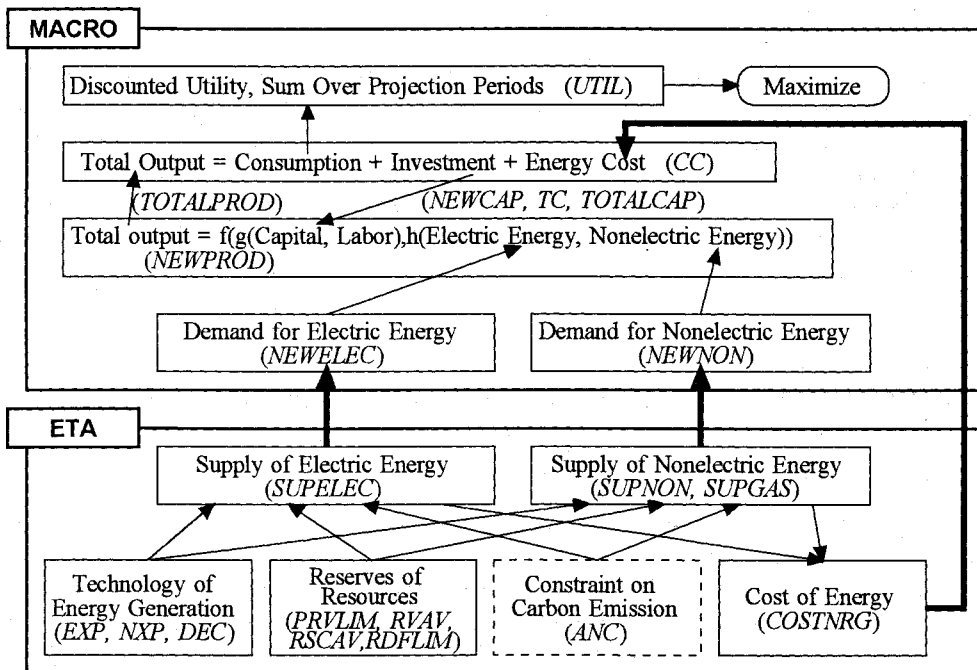
In coping with account system of environmentally sustainable product, ESP, the authors use the skeleton of the dynamic optimization model, "Global 2100". This model was originally presented by Alan S. Manne and Richard G. Richels (1992). Fig.4 and Fig.5 show the structure of the original Manne and Richels model and its constraints. In this original model, the world is divided into five regions: the United States (USA), other OECD nations (OOECD), the former Soviet Union and Eastern Europe (USSR), China, and rest of the world (ROW). Manne and Richels model consists of two sub models; ETA, an energy technology assessment model, and MACRO, a macroeconomic production function describing the balance of the economy. The former sub model consists of various electric energy and nonelectric energy generation technologies, reserved fossil fuels and aggregated macroeconomic production function. In this

paper, the authors discriminate Japan from OECD instead of the original Manne and Richels model. When using this six-region model, the authors revise the model structure and its various parameters especially in the gas trade sector which is not discussed in the original model.

These two sub models are linked in the process in two sets of bold lines as shown in Fig.4; the first implies the equilibrium of electric and non electric energy, and the second does costs of energy in the energy production costs and energy supply-demand. Energy supplies are originated from both exhaustible hydrocarbon resources and those developed by backstop technologies. Each energy supply technology has the costs and the carbon emissions per unit of activity level. There are upper bounds on the speed of introduction of new technologies and lower bounds on the decline rate of supplied volumes.

Global 2100 is benchmarked against the base year of 1990, and the projections cover every ten-year time intervals since 2000 till 2100. The intertemporal model is operated to maximize the utility, sum of discounted logarithms of consumption, based on the traditional concept of marginal utility diminishing, subject to available reserved resources. It is assumed that producers and consumers are able to predict the factor counted in total output summation sufficiently, and anticipate the degree of the scarcities of energy and the environmental disasters in the future.

3.2 Environmental Goods Introduced in Global Model



Note: [dashed box] is available in the case of the carbon emission reduction scenario. 'Italic' shows the name of constraint.

Source: Manne and Richels (1992)

Figure 4. Framework of Original Global 2100

Here, attached modules in modified Global 2100 are shown in this section, which are able to account for damage costs due to environmental pollution and other environmental externalities as shown in Fig.6.

(1) Evaluating External Diseconomies

External diseconomies mean that while making use of fossil fuels generates the beneficial economic activities, various discharged pollutants influence the economic activities inbeneficially. Among the external diseconomies, likely appeared, the authors select the impacts of air pollutants such as nitrogen oxide (NO_x) and sulfur oxide (SO_x), and greenhouse gases, carbon dioxide (CO_2). Depletion of non-renewable resources and accumulation of radioactive wastes from atomic power generations are also considered because "Global 2100" includes these energy supply technologies.

Conventional model analyses have focused on only the market based damages which are regarded as the decrease of production account. On the other hand, the authors propose that both of market and non market based damages should be evaluated in the equation of the total output summation. The typical difference between the authors' and the past researches is that the damages are regarded as posterior subtraction after production stage or negative inputs in production process. As shown in Fig.7, the manner of using separate costs as mentioned above serves the purpose of environmental accounting. This implies that global environmental

Name of constraints :	Contents [Dimension]
MACRO Submodel	
UTIL	: Discounted utility, sum over all projection periods [-]
CC	: Allocation of total output capacity among expenditure categories [tri. \$]
NEWCAP	: New capital stock, excluding energy sector [tri. \$]
TC	: Terminal condition on investment and capital stock [tri. \$]
NEWPROD	: New vintage production, excluding energy sector [tri. \$]
TOTALPROD	: Total production, excluding energy sector [tri. \$]
TOTALCAP	: Total capital stock, excluding energy sector [tri. \$]
NEWLEEC	: New vintage demand for electric energy [TkWh]
NEWNON	: New vintage demand for nonelectric energy [EJ]
ETA Submodel	
SUPELEC	: Supply of electric energy [TkWh]
SUPNON	: Supply of nonelectric energy [EJ]
SUPGAS	: Supply of gas [EJ]
EXP	: Maximum expansion of electric technologies [TkWh]
NXP	: Maximum expansion of nonelectric technologies [EJ]
DEC	: Maximum decline of electric technologies [TkWh]
PRVLIM	: Production of exhaustible hydrocarbon resources [EJ]
RSAV	: Proved reserves available [EJ]
RSCAV	: Undiscovered reserves available [EJ]
RDFLIM	: Resource depletion limit [EJ]
*ANC	: Annual carbon limit [bil. tC]
COSTNRG	: Cost of energy [tri. \$]

Note: Constraint with * is available in the case of the carbon emission reduction scenario.

Source: Manne and Richels (1992)

Figure 5. Constraints of Original Global 2100

disasters do not affect directly the magnitude of production activities in themselves, but these damages are evaluated in the economic system in sustainable society aiming growth through Hicksian income. This evaluation method of environmental damages has advantages over the conventional method as follows. In the modified model, environmentally weighted welfare expressed by eq. (1) is examined by using sensitivity analysis with respect to original unit cost in dollar per unit pollutant as sub parameter. The process of subtraction of market/non market damage costs has wide range applicability in the system of environmental economic accounting such as SEEA. On the contrary, market damage and non market damage are distinguished in MERGE. The former damage is estimated to be the decrease of production activities induced by global warming. The latter damage is evaluated as the WTP to avoid the global warming

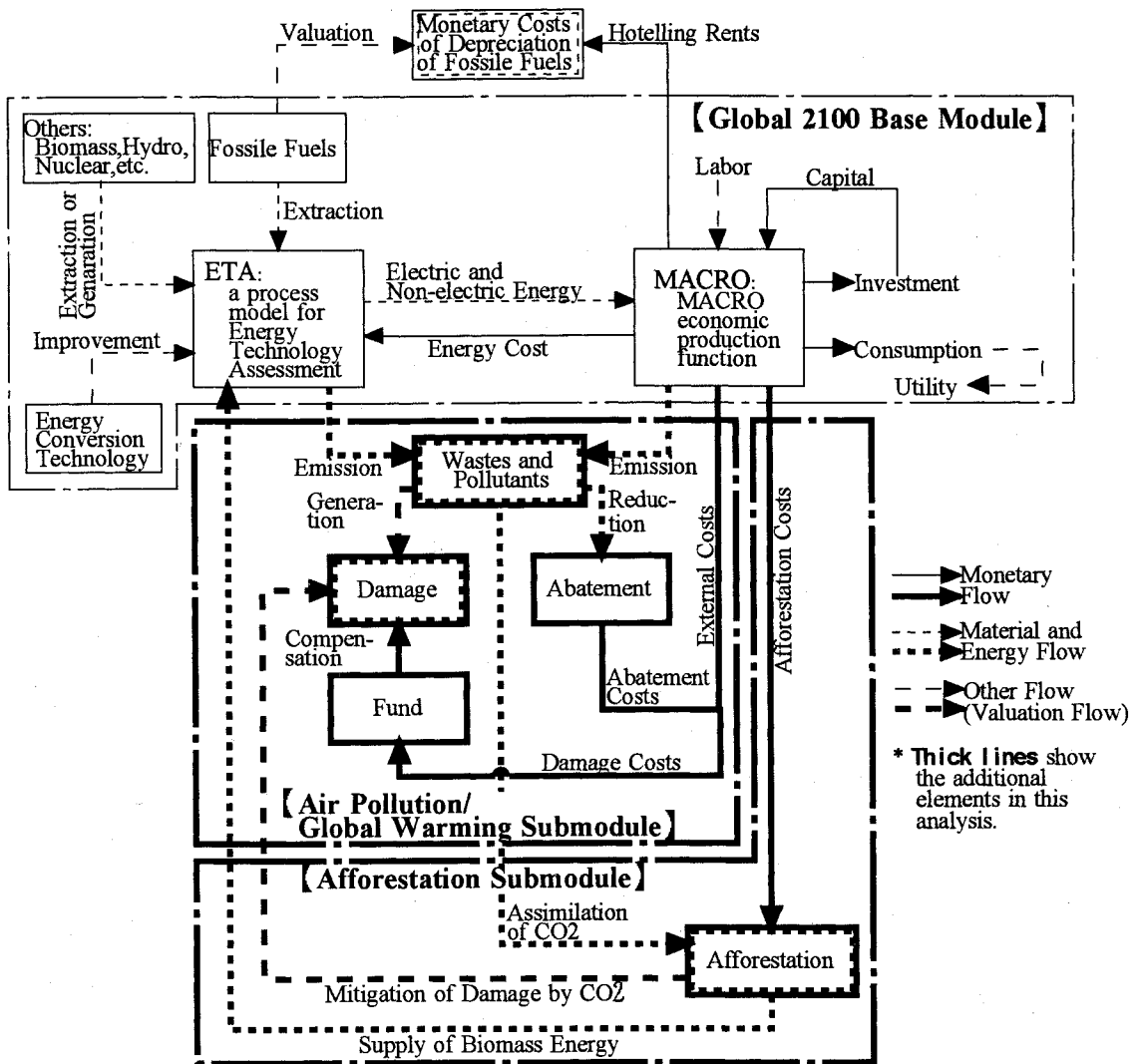


Figure 6. Revised Model Structure

in the utility function. So far as evaluating damages based on the accounting system, WTP cannot be accepted in the same time. In this paper, the authors evaluate the non market based damages in the same manner as the market based damages in the account system.

Abatement Costs and Damage Costs by Pollutants The authors evaluate abatement costs and damage costs derived from pollutant emissions discharging into the environment by using the modified model. One of the module in this modified model is named as "Air Pollution / Global Warming Submodule." When gases such as CO₂, NO_x and SO_x accumulate in the

General optimization model:
 Max $\sum_t udf_t * U(C_t)$
 s.t. $aK_t^b E_t^d = C_t + I_t + E_t * ep$
 $K_{t+1} = K_t + I_t$
 Variables;
 C:consumption, K:capital stock, E:energy supply, I:investment
 Parameters;
 ep:energy price, udf:utility discount factor

Assumption:damages are only caused by energy use
 f(E_t):damage factor to production function
 g(E_t):damage costs

A) Revised production function;
 Max $\sum_t udf_t * U(C_t)$
 s.t. $aK_t^b E_t^d f(E_t) = C_t + I_t + E_t * ep$
 $K_{t+1} = K_t + I_t$
 Defined H as follows;
 $H = \sum_t udf_t * U(C_t) + r_{t+1}(K_{t+1} - K_t - aK_t^b E_t^d f(E_t) + C_t + E_t * ep)$
 r_t:Lagrange multiplier
 From one of the conditions of optimality, $\partial H / \partial E_t = 0$
 $aK_t^b (E_t^d \frac{df(E_t)}{dE_t} + f(E_t) \frac{dE_t^d}{dE_t}) = \frac{dE_t * ep}{dE_t}$
 marginal products of energy + marginal products of damage = marginal costs of energy

B) Revised summation;
 Max $\sum_t udf_t * U(C_t)$
 s.t. $aK_t^b E_t^d = C_t + I_t + E_t * ep + g(E_t)$
 $K_{t+1} = K_t + I_t$
 Defined H as follows;
 $H = \sum_t udf_t * U(C_t) + r_{t+1}(K_{t+1} - K_t - aK_t^b E_t^d + C_t + E_t * ep + g(E_t))$
 r_t:Lagrange multiplier
 From one of the conditions of optimality, $\partial H / \partial E_t = 0$
 $aK_t^b \frac{dE_t^d}{dE_t} = \frac{dE_t * ep}{dE_t} + \frac{dg(E_t)}{dE_t}$
 marginal products of energy = marginal costs of nergy + marginal costs of damage

Figure 7. Difference between Production Function and Total Output Summation in Evaluating Damages

Fuels	SOx[t-SO ₂ /EJ]	NOx[t-NO ₂ /EJ]	CO ₂ [t-C/EJ]
Coal	2,200*10 ³	245*10 ³	24,120*10 ³
Oil	480*10 ³	155*10 ³	19,940*10 ³
Gas	0	115*10 ³	13,740*10 ³

Source: Hondo and Uchiyama (1993)

Table 1. Pollutant Release Coefficients by Fuel Forms

Nations	Amount of damage [bil.\$]	Pollutants		Damage per pollutant		
		SOx [1000t]	NOx [1000t]	SOx [\$/SOx]	NOx [\$/NOx]	
United States (1990)	53.5	21,060	19,380	1,570	1,050	Daly and Cobb
Netherlands (1986)	0.5- 0.8	262	576	770-1,240	520- 830	Opschoor
Germany (1985)	19.3-21.5	7,785	3,565	1,900-2,120	1,270-1,410	Schulz
in the Model				1,520	1,020	

Source: Daly and Cobb (1994), Pearce et al. (1989), and OECD (1993)

Table 2. Estimated Value of Damage and Emissions of Pollutants

year	1991-2000	2001-2010	2011-2020	2021-2030	
CO ₂ [\$/tC]	7.3(0.3-65.9)				Nordhaus
	30-35				Ayres and Walter
	5.3	6.8	8.6	10.0	Nordhaus
	10-12	12-14	14-18	18-22 (3.4-57.6)	Peck and Teisberg
	20.4 (6.3-47.7)	22.9 (7.2-53.8)	25.4 (8.1-60.3)	27.8 (8.8-66.2)	Fankhauser
	in the Model: 30[\$/tC]				
NOx [\$/tN]	2,940 (800-7,465)	3,433 (948-8,749)	3,925 (1,090-9,652)	4,571 (1,241-11,419)	Fankhauser
	in the Model: 1,200[\$/tNOx]				

Source: Pearce and Fankhauser (1993)

Table 3. Estimated Damage by Global Warming

atmosphere, the people will face serious consequences such as global warming problem and so on. The shared expenses due to the impacts of these gases are categorized into abatement costs as the "ex ante," and damage costs as the "ex post." Subtracting these two costs from the national income leads to the amount of ESP as shown in eq. (1).

These abatement costs correspond to the maintenance costs required for conserving air quality previous to discharging. In conventional economic system, abatement costs even for desulphurization or other prevention processes have been simply recognized as one of the monetary flows of general equipment costs. In this model, these abatement costs are clearly distinguished from general equipment costs. Here, the authors simplify abatement costs to be constant to proportional to the quantities of pollutants as shown in Table 1, ignoring change of marginal cost respective mass of the pollutants. The abatement costs per unit pollutant are reckoned to be equivalent to those observed in several power plants (Hondo and Uchiyama,

1993); abatement cost for NO_x is 8,620 dollars per tonne of NO_x , and for SO_x is 3,793 dollars per tonne of SO_x . Furthermore, it is assumed that the costs per unit pollutant per year are improved by the same rate as the index of the autonomous energy efficiency improvement (AEEI).

The remains are left in air, and then result, to some extent, in environmental degradation even when pollutants comply with the environmental standard set by governments. Therefore, possible damage costs pertinent to the remain pollutants discharged to the environment are taken into account, besides the actual abatement costs. The damage costs per unit of NO_x and SO_x are shown in Table 2, where damage costs are also constant to the mass of the pollutants. Of course, the damage costs of global warming due to NO_x and CO_2 are considered because of their high global warming potential. The damage costs by global warming estimated by Pearce and Fankhauser (1993) are used. The damage costs of NO_x is 2,220 dollars per tonne of NO_x , considering the sum of the damage costs derived from both air pollution and global warming.

Either *ex ante* or *ex post* costs having lower marginal cost is selected generally in simulation. In this paper these external costs are regarded to be constant, therefore either of the two types of costs responsibility is chosen in any time. In order to correct in the appropriate operations in simulation derived from this oversimplification of marginal costs being constant, the removal ratios of pollutant emissions are assumed in advance. In Japan, the removal ratio of SO_x and NO_x in emission treatment facilities in 1987 was estimated as 71.2 % and 39.7 % respectively (Science and Technology Agency, 1993). These ratios in the developed nations are supposed to be 70 % for SO_x and 40 % for NO_x ; nearly 0 % in developing countries. Since carbon elimination is said to be very expensive, so the authors regard the removal ratio of CO_2 in engineering facilities as zero.

Besides those costs above mentioned, the costs for disposal of the wastes of nuclear power station are assumed to be the same as the generation costs of electricity in the nuclear power station.

Depletion of Non-renewable Resources Economic welfare should be depreciated in terms of monetary flow equivalent to less availability of gaining those non-renewable resources liable to have been consumed by prior generations. In the conventional approach, the national income by the optimization model has constraints of limited reserve of exhaustible resources. This approach deals with the depreciation of those resources in the manner of Hotelling Rents (Hartwick, 1990). Thus the national income simulated by Global 2100 assesses the depreciation of non-renewable resources: additional improvement is not required.

Sustainable income is obtained in eq. (1), when above costs caused by external diseconomies are extracted from the conventional income, GDP. Additional constraints and equations, which are all linear functions, have never affected the conditions of solution required for the optimization technique. In other words, the convexity of a set of solutions is not failed.

(2) Afforestation Submodule

Forests, especially tropical rain forests, have important roles to absorb carbon and to stabilize the global climate (IPCC, 1994). Since even these types of benefits derived from forests are not evaluated in the conventional economic account system, afforestation programs are liable to be out of policy making. Paying attention to the expected relatively high cost performance of afforestation, "Afforestation Submodule" is introduced into the modified model. Here, two

	Carbon absorption ratio [tC/km ² /yr]	Growing periods [yr]	Potential afforestation area [km ²]	Available afforestation area [km ²] **
USA	600	20	450,000	112,500
Japan	600	20	26,500 *	6,625
OECD	400	20	1,543,500	385,875
China	600	20	860,000	215,000
USSR	360	20	1,220,000	305,000
ROW	990	20	3,970,000	992,500

Notes: * Estimated from the potential afforestation area in OECD-Pacific region

** Supposed to be 25 % of potential area

Source: Okada et al. (1993)

Table 4. CO₂ Absorption Ratio and Afforestation Area in Model

	Region A	Region B
Initial planted costs	438- 4,287 [\$ /ha]	337- 3,293 [\$ /ha]
Initial costs and maintenance costs *	1,752-17,148 [\$ /ha]	1,348-13,172 [\$ /ha]
Annual afforestation costs **	138- 1,351 [\$ /ha/yr]	106- 1,038 [\$ /ha/yr]
Value chosen in this model	750 [\$ /ha/yr]	570 [\$ /ha/yr]
Supply of biomass per forest area	156 [t/ha]	205 [t/ha]
Energy potential of biomass	15.0 [GJ/t]	

Notes: Region A: USA, Japan, OECD and USSR

Region B: China and ROW

*: Maintenance cost is supposed to be 3 times of newly planted cost.

** : Supposed to be 20 years for growing periods and annual 5 % discounted rate.

Source: Okada et al. (1993)

Table 5. Afforestation Costs and Biomass Energy Supply

functions of absorption of carbon emission and supply of biomass energy are considered respectively.

CO₂ Absorption Capabilities and Costs in Afforestation Program Trees in growing periods have capability of CO₂ absorption, varying according to species and lifestages of trees in various geophysical condition. Physical data in afforestation are shown in each region in Table 4.

The available afforestation areas are estimated to be 25%, while the maximum afforestation area per year is 1% of the potential areas as in the approach of Okada *et al.* (1993). Marginal costs of afforestation seem to increase with respect to the additional unit afforestation. However the authors use constant afforestation costs per unit of afforestation area. The afforestation costs used in this model are considered to be the total discounted costs of both initial costs and maintenance costs of afforestation practices.

It is reasonable that the above mentioned costs should be subtracted from the national income in the process of calculation of ESP. On the contrary, by afforestation, the people obtain both benefits of less expensive absorption of CO₂ and increased biomass energy supply from grown-up trees.

Abatement Costs	: $ABC(t) = \sum_{pol} (ENE(t)*ef(pol)*er(pol)*ac(pol))$
Damage Costs	: $DAC(t) = \sum_{pol} (ENE(t)*ef(pol)*(1-er(pol))*dc(pol)) - AC(t)*dc("CO2")$
Total afforestation Areas	: $TAA(t+1) = TAA(t) + (NAA(t) + NAA(t+1))*5$
Afforestation Costs	: $AFC(t+2) = (NAA(t)*5 + NAA(t+1)*10 + NAA(t+2)*5)*aca$
Absorbed CO2	: $AC(t+2) = (NAA(t)*5 + NAA(t+1)*10 + NAA(t+2)*5)*caa$
Deforestation Areas	: $RA(t+3) = RA(t+2) + (NAA(t) + NAA(t+1))*5 - (DA(t+2) + DA(t+3))*5$
t: time period (time span: 10 years)	Variables
pol: pollutants (CO ₂ , SO _x and NO _x)	ABC: abatement costs
	AC: absorbed CO ₂ by afforestation
	AFC: afforestation cost
	DA: deforestation areas
	DAC: damage costs
Parameters	ENE: energy consumption
ac: abatement costs per pollutant	NAA: newly afforested area
aca: afforestation costs per area	RA: afforestation areas – deforestation areas
caa: absorbed CO ₂ per afforestation area	TAA: total afforestation areas
dc: damage costs per pollutant	
ef: pollutant emissions factor	
er: ratio of eliminated pollutants	

Notes: Variables, ABC, DAC, and AFC, are deducted from GDP in order to calculate ESP. Variable, DA, affects the supplies of nonelectric energy.

Figure 8. New Constraints in order to introduce the Sustainable Society

Parameters Setting on Grown-up Trees As mentioned above, grown trees provide the biomass energy. When grown-up trees are used for the biomass energy, the carbon stored in the trees is released to the atmosphere. But in this model, released CO₂ are instantaneously absorbed by other planted trees on site again. Then, the carbon emission from the biomass energy becomes zero. In this model, the annual maximum deforestation area is proposed to be 0.5% of the potential afforestation area. Table 4 shows the trees and their biomass energy from unit forest area.

When afforestation is carried out in all available areas based on the assumption in this paper, total CO₂ absorption becomes 28.9 billion tC, which is four times more than the emissions in 1990. While the available supplied biomass energy becomes 5,600 EJ, which is 17 times as much as the primary energy consumption in 1990.

As these new constraints on afforestation program are also represented by linear functions, adding them do not fail to maintain the convexity of this model. The constraints in "Air pollution / Global warming Submodule" and "Afforestation Submodule" are shown in Fig.8.

4. Outputs of Simulation and Analyses

Here, the consumption, instead of the national income such as GDP, is examined in order to discuss the scale of the economic activities. Modified Global 2100 model is operated by using numerical simulation General Algebraic Modeling System (GAMS), nonlinear optimization model technique (Brook *et al.*, 1992).

4.1 Outputs from Conventional Account System

At first, the authors show the output of the reference scenario. In the reference scenario, the abatement costs of SO_x and NO_x and the disposal costs for nuclear waste are only taken into account in the traditional manner. National income of the reference scenario also accounts for the monetary costs of depletion of fossil fuels but not for other primary damage costs by pollutants.

(1) Outputs of Reference Scenario

The carbon emission in the reference scenario is shown in Fig.9-(a). In the year 2100, the total amount of the global carbon emission will grow up to 38.7 billion tC. This value is about six times of the carbon emission in 1990, and its annual growth rate is about 1.70 %/year. In the same figure, it is recognized that the carbon emission growth in developing countries is more than that in developed nations.

Fig.9-(b) represents the trend of the consumption level in each region. In the world, the consumption will become 158 trillion dollars in 2100: 2.01 %/year growth rate. Incidentally, GDP in 2100 is 191 trillion dollars, and it is about 8.5 times compared with 1990.

In Japan, carbon emissions, consumption level and GDP in 2100 will be 5.7, 7.8 and 7.3 times higher of those in 1990, respectively. But, the ratio of each indicator of Japan to the world total is decreasing throughout the 21st century. Emissions of SO_x and NO_x in Japan are also increasing, therefore the abatement cost of these pollutants in 2100 is about 1.3 times of that in 1990. On the other hand, the abatement cost in the United States is reduced by

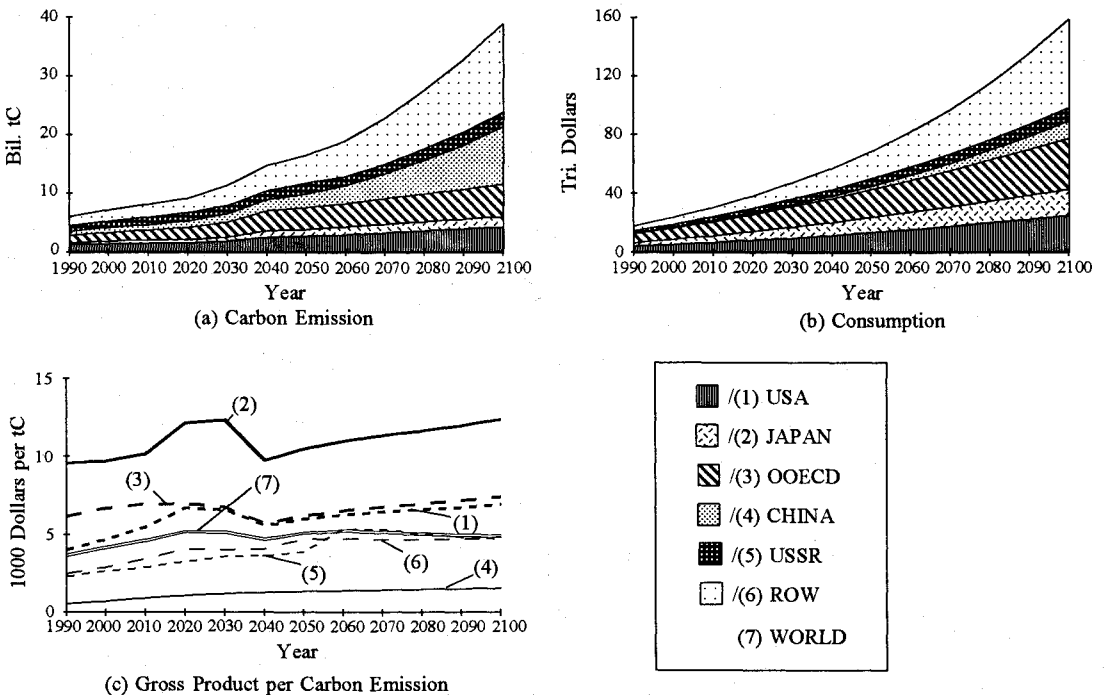


Figure 9. Output from Reference Scenario

about 40% until 2100.

Gross product per carbon emission in the period of 1990 - 2100 is shown in Fig.9-(c). In Japan, this index is improved by about 0.23 %/year. And in China the value is improved by about 0.99 %/year, which is the highest in the world. But its value estimated for the year of 2100 will not be able to reach the production performance of Japan in 1990 in terms of carbon emission. In other developing countries, this index at the end of the 21st century will have only reached to the level of USA in 1990s, the lowest among the developing countries group.

The difference of output in the reference scenario between original Global 2100 and this modified model rarely exists; the difference of annual growth rate of carbon emission and GDP is 0.03 %/year and 0.07 %/year respectively.

(2) Lower Economic Growth Rate Modification

Lower economic growth rate is an option to be selected in environmentally sound policy-making. In this scenario, it is assumed that the economic growth rate in each region is half as much as the value in the reference scenario. Estimation of carbon emission in 2100 being 10.7 billion tC reveals that low economic growth is very effective to reduce the CO₂ emission. Unfortunately, the growth ratio of the consumption level in this scenario will decrease 0.85 %/year compared with the one in the reference scenario (See Fig.10-(b)).

4.2 Performance from Environmentally Sustainable Economic System

In this section, the authors show the outputs of the modified global simulation associated with a normative rule of internalizing environmental damages in environmentally sustainable society. The standard damage costs scenario (S scenario) has the average costs examined in several developed countries as shown in the previous chapter. The high damage cost scenario (H scenario) means that the damage costs are twice as much as those of the S scenario. And, the damage costs of the low damage cost scenario (L scenario) are half of the S scenario. These types of scenarios indicate that all damage costs are not paid in market but counted in the environmental accounting system for long-term policy making. "Relative ratio" in the following discussions means "the value compared with the reference scenario".

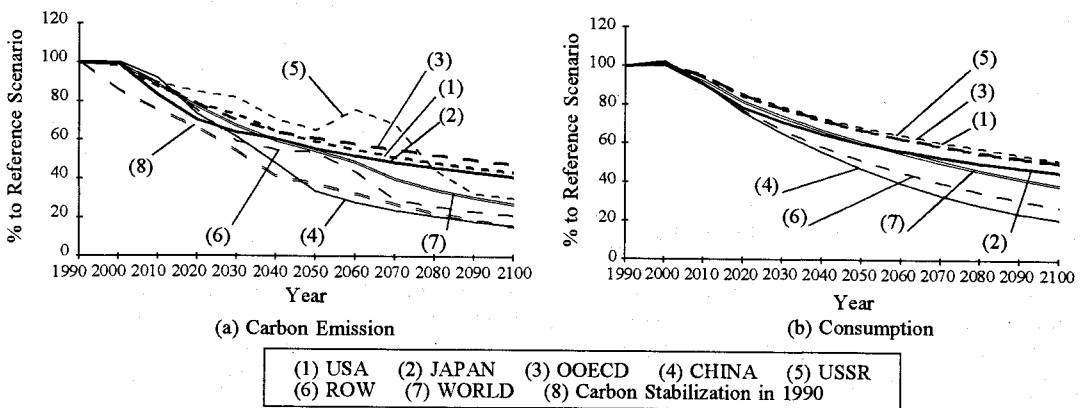


Figure 10. Output from Lower Economic Growth Rate Scenario

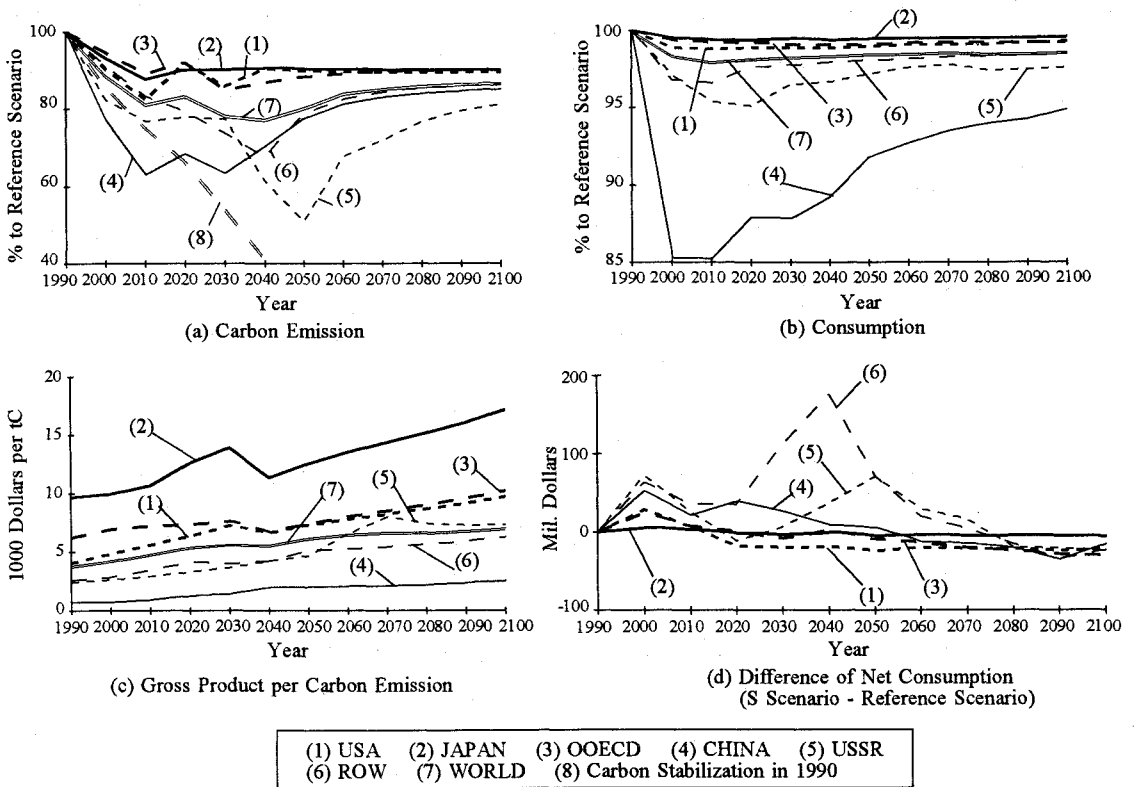


Figure 11. Consequence of Standard Damage Costs Scenario

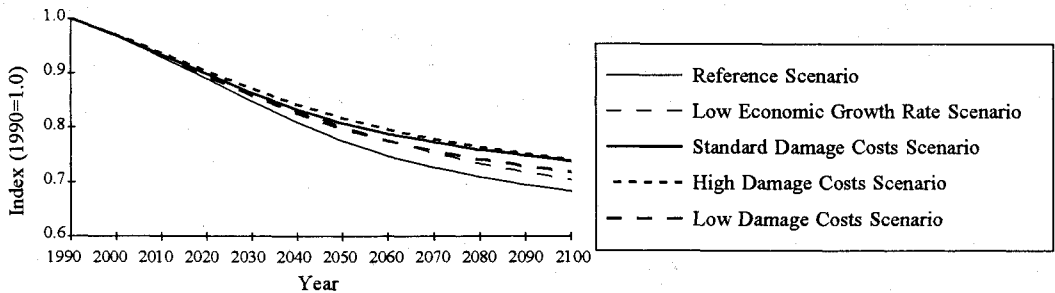


Figure 12. Trends of Reserved Fossil Fuels

(1) Standard Damage Costs Scenario

The S scenario shows that the relative ratio of the world total carbon emission is at the minimum 77.4% in the year 2040. And, the carbon reduction ratio in 2100 compared with the reference scenario is 13.2% (See Fig.11-(a)). In Japan the relative ratio of carbon emission is of minimum 87.6% in 2010, and in 2100 is 90.1%. The tendency of carbon reduction ratio compared with that in the reference scenario in the world as shown in Fig.11-(a) is interpreted as follows. Up to the middle of the 21st century, coal as fuel is replaced by oil or gas in energy

consumption. However, after that, because of the shortage of liquid or gas fuels, coal will be consumed in a large amount, resulting in less carbon reduction compared with the reference scenario.

The world consumption level is depressed to 2.0 % (2010) - 1.4% (2100). In Japan, the consumption level is reduced by about 0.5% of that in reference scenario throughout the 21st century. But the reduction of the consumption level in developing countries is fairly larger than that in developed nations. Especially distinctly low level of relative value of consumption in China is to be judged as disadvantageous to developed countries with 10 % difference compared with the reference scenario.

When the net consumption level, defined as the consumption minus external damage costs, in each region in this scenario is compared, it is deduced that the amount of net consumption in the S scenario at the beginning of 21st century is larger than in the reference scenario. In the simulation in the conventional account system, only the gross consumption has effect on the next step calculation of production and distribution, however damage costs in each step may be stored in the accumulator out of core production module. In the reference scenario, the apparent net consumption is calculated as the term of the consumption minus unpaid damage costs after optimizing process of the model. In the case of this S scenario, the net consumption corresponds to the damage-adjusted consumption, because damage costs have already taken into account in the optimal simulation. After the middle of 21st century, indeed, the amount of net consumption in the reference scenario is larger than in this S scenario. However, the sum of the discounted net consumption throughout the 21st century has inverse trend, that is greater value in the S scenario than in the reference scenario.

Decreases in discharged pollutants such as SO_x and NO_x throughout the 21st century are from 13.3 % to 57.0 % compared with those in the reference scenario. Whether the ratio of the damage costs to the abatement costs is larger or not, taking damages into account is judged incentives to reduce pollutants by means of changing energy mix into cleaner energy selection. The discharged pollutants after the middle of 21st century are not so much reduced compared with the reference scenario, because of the depletion of less expensive liquid and gas fuels with low degree of carbon per unit calorie by the middle of 21st century.

The trend of the index of efficiency of carbon emission (gross product per carbon emission) is shown in Fig.11-(c). Comparing Fig.11-(c) with Fig.9-(c) in the reference scenario, it is clear that the values of the efficiency index in the late era of the 21st century in this S scenario become larger in each region. Each region gains higher efficiency of production to carbon emission by means of recognizing signals of depreciation due to environmental damage in the national income system and then changing energy mixture.

Fig.12 represents the change of the stock of fossil fuels reserved in the world. The non-renewable resources in the S scenario are liable to be more reserved than in the reference scenario. Even supposing low economic growth, depletion of the fossil fuels in terms of the so-called Hotelling rents is larger than that in the S scenario. Enhancing economic repercussion from assessed environmental damages become a superior choice prior to merely cutting economic growth down. Because, first, the net consumption level in the S scenario is more than that in the reference scenario: economic welfare becomes greater. Second, the depletion of non-renewable resources in the S scenario is less than that in the reference scenario.

(2) High Damage Costs Scenario

The output of the high damage costs scenario is shown in Fig.13. In this scenario, carbon emission increases by 1.46 %/year, which is 0.09 % point less than the S scenario. The relative

ratio of the total global carbon emission is minimum at 67.9 % in 2040, with an average of 73.7 % in the 21st century (Fig.13-(a)). The relative ratio of total consumption level in the world is of minimum 96.5 % (in 2010), and is 97.3 % in 2100. The shrinkage in the consumption level are almost twice as much as that in the S scenario. Drop of the consumption level in China is the most distinct in the world. This may be due to: Although the highest economic growth rate is foreseen in China, this high economic growth will not be compatible with environmental conservation. Moreover, in China, because coal is regarded as the main energy source, it seems to be difficult to reduce carbon emission without scaling down the economic activity compared with that in the reference scenario. In the case of developed nations, the relative ratio of the consumption level compared with the reference scenario is from 99.1 to 97.7 % every year, which is much higher than developing countries. This implies that since the estimated values of damage costs per pollutants are based on the observed damage in several developed nations mentioned above, required expenditures for mitigating environmental damages become very expensive for developing countries. Obviously, emission of air pollutants in this H scenario is less than the S scenario.

In the case of the H scenario, larger amount of the net consumption level is calculated than that in the S scenario (See Fig.13-(d)). The higher the damage cost increases in the H scenario, the greater incentives for stricter control to remove pollutants become. In another word, the periods when the net consumption level in this scenario exceed the one in the reference scenario is longer than that in the case of the S scenario. In developing countries, almost throughout

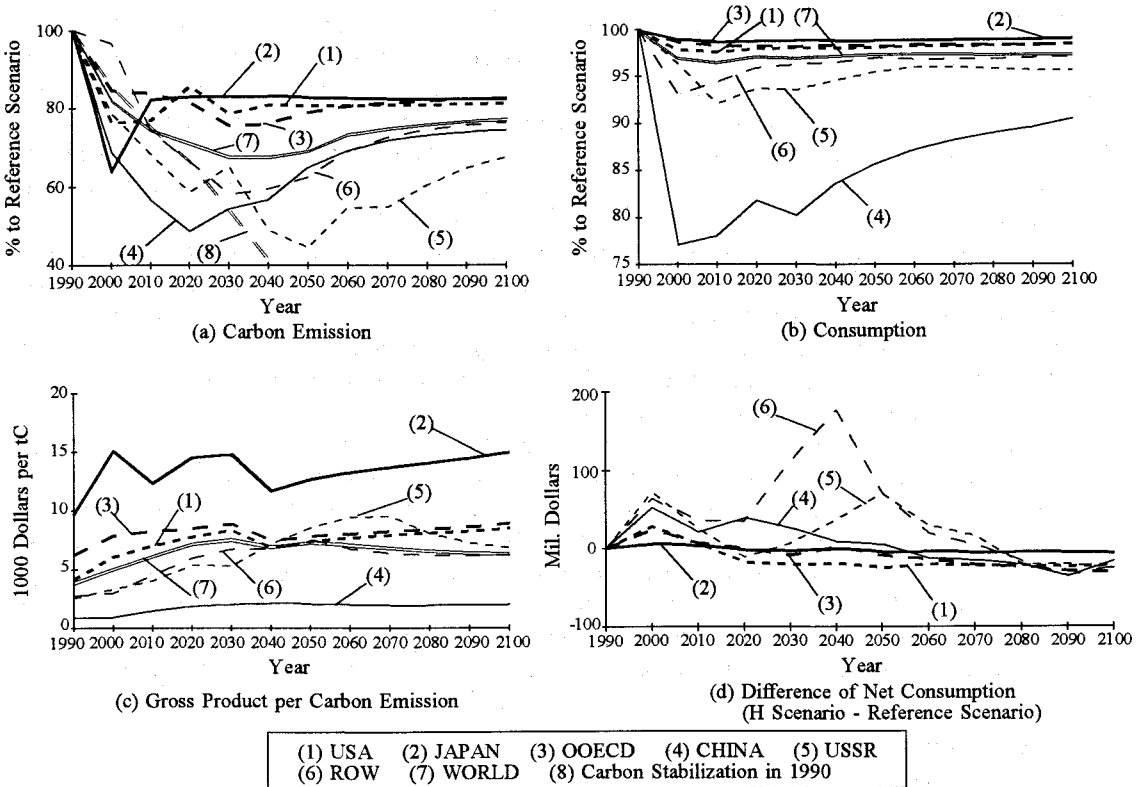


Figure 13. Consequence of High Damage Costs Scenario

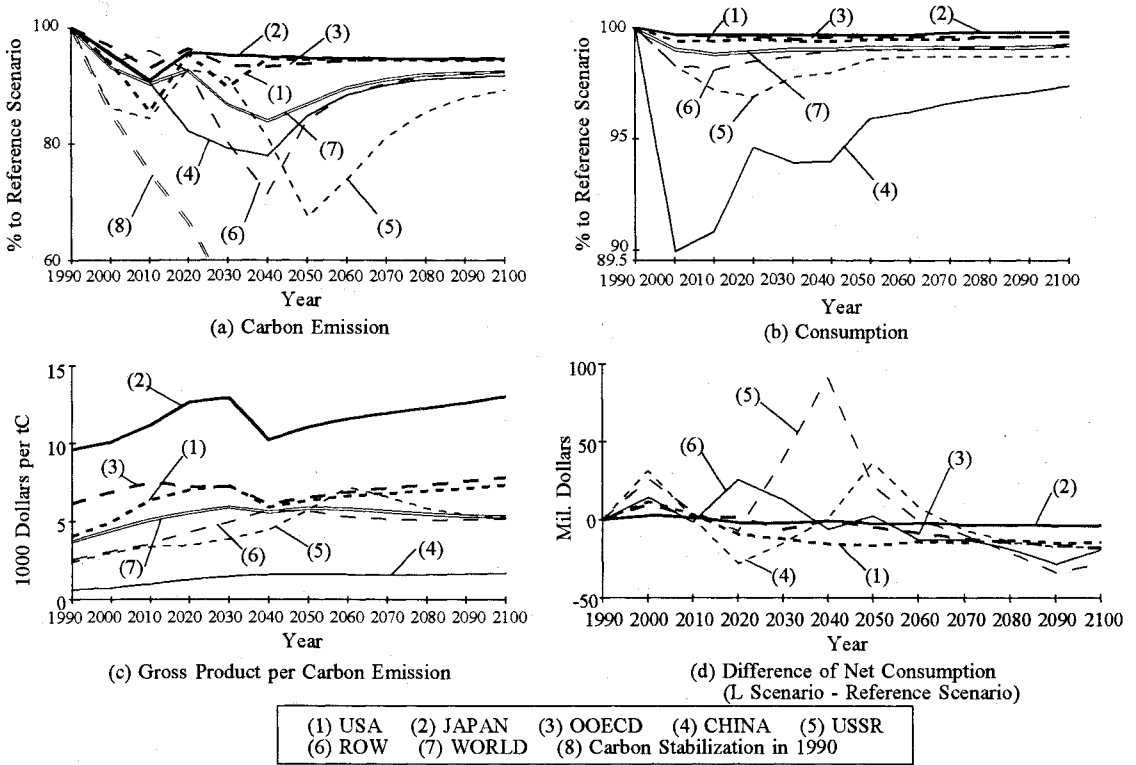


Figure 14. Consequence of Low Damage Costs Scenario

the 21st century, the net consumption level in this scenario exceeds the one with the reference scenario. The difference in the sum of the present value of the world net consumption in this scenario to that in the reference scenario is about four times as much as the one in the case of the S scenario.

(3) Low Damage Costs Scenario

In the case of the L scenario, relative ratio of the consumption level in developing countries except China can keep the yearly growth rate of consumption at -3.1 % lower than that in the reference scenario in the most inferior year. Even in this scenario, the drop of the annual consumption in China is sometimes more than 5 %. In this scenario, relative ratio of the total global carbon emission compared with the reference scenario is 90.6 %/year, but minimum relative ratio of world carbon emission is 84.2 %/year (in 2040). Fig.15 represents the correlation between total damage costs and total carbon reduction throughout the 21st century. From this figure, it is proved that the higher the damage costs, the less the efficiency of carbon reduction (carbon reduction per unit of damage cost) becomes. As Fig.14 shows, this scenario seems to be acceptable by the countries and the regions in collaboration with each other against global warming. Even if all damage costs are not paid by polluters as in this L scenario, considerable large amount of air pollutants can be effectively cut down at the beginning of the 21st century.

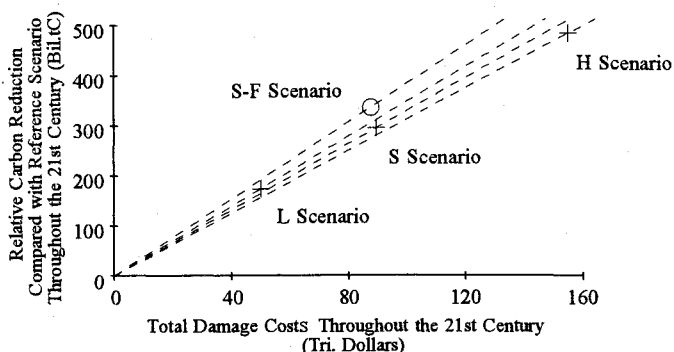


Figure 15. Correlation Between Total Damage Costs and Carbon Reduction throughout the 21st Century

This scenario has a larger amount of net consumption than the reference scenario at the beginning of twenty-first century. Focusing on the difference of sum of the discounted global net consumption throughout the 21st century in this L scenario from that in the reference scenario, the value in the case of the L scenario is quarter of the value in the case of the S scenario.

4.3 Effectiveness of Afforestation Policy in Scenario

When afforestation module is operated in the dynamic simulation model in the reference scenario, no action of afforestation in each region is chosen in simulated reference world for a rational option. That is to say, effectiveness of carbon absorption is not appropriately assessed in the conventional economic system. On the contrary, in the environmentally conscious society where the ESP is introduced as in the S scenario, afforestation activities are recognized at the economic level of 0.016 % of the gross total production in average throughout the 21st century.

Fig.16 represents the outputs of introducing afforestation policy in the S scenario, named as the S-F scenario. In this case, the afforestation is seemed to be carried out in each region. As a result, the relative reduction of carbon emission over the S scenario has mean and maximum of 0.42 billion tC/year and 0.80 billion tC/year in 2050 respectively. Moreover, the consumption level in the S-F scenario compared with the S scenario is greater by 3 to 31 billion dollars per annum, although the afforestation cost is subtracted from the national income. These results imply the benefit from the afforestation is more than the cost for afforestation.

A program of afforestation in developed nations and former USSR is implemented at the end of 21st century in the dynamic optimization. On the other hand, the developing countries are put into practice to be performed from the beginning to the end of 21st century continuously. The reason of these differences is attributable to apprehension of either carbon absorption or biomass energy supply. In developed nations, afforestation is regarded as the means for carbon absorption. In contrast, developing countries consider it for both carbon absorption and supply of biomass energy.

In the S-F scenario, all areas in the maximum potentially served for forest are not covered by afforested vegetation in developed nations, although in the developing countries all areas are almost completely covered. The higher the damage costs are, the wider the afforestation area in developed nations is. Consequently, the H scenario with afforestation has larger amounts

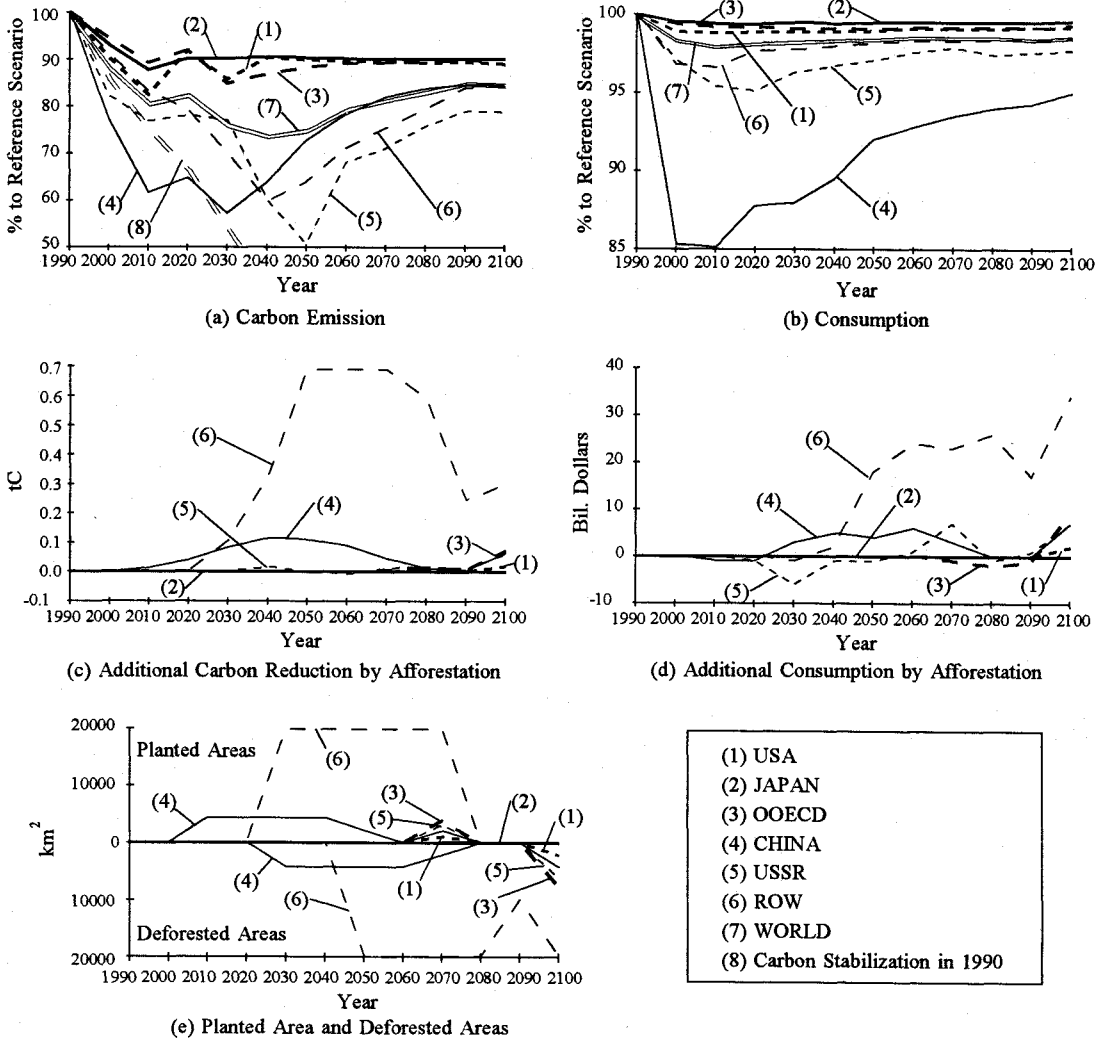


Figure 16. Output of Standard Damage Costs with Afforestation Scenario

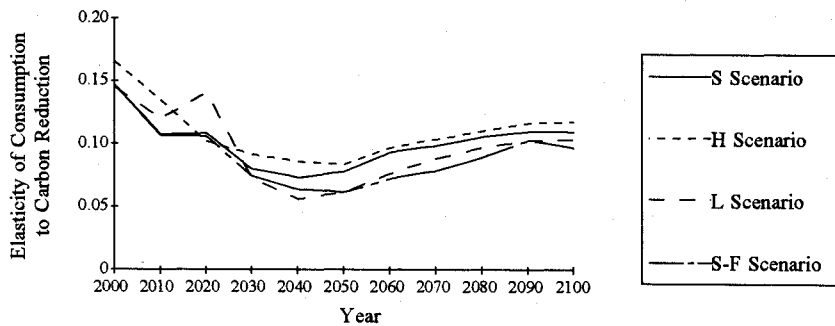


Figure 17. Elasticity of Consumption to Carbon Reduction in Each Scenario

in terms of both the carbon reduction and the net consumption level than the S-F scenario although the marginal carbon reduction is diminishing with damage cost. In environmentally sustainable society, introducing environmental preservation activities such as afforestation will be more beneficial in terms of the carbon reduction and supply of biomass energy even if high damage costs are imposed.

Finally, the authors analyze the elasticity of consumption to carbon emission. The elasticity is defined as follows;

$$elasticity = \frac{(CONS - CONS_{reference})/CONS_{reference}}{(CO_2 - CO_{2reference})/CO_{2reference}} \quad (2)$$

CONS, *CONS_{reference}*, *CO₂*, and *CO_{2reference}* are consumption, consumption in the reference scenario, carbon emission, and carbon emission in the reference scenario, respectively. The higher the damage costs are, the higher the elasticity is. This implies that carbon reduction in the higher damage costs scenario is less effective than that in the lower damage costs scenario. The value of elasticity in the standard damage costs scenario with afforestation is lower than that in the low damage costs scenario without afforestation (See Fig.17).

5. Conclusions

In this paper, the authors attempt to improve the conventional account system which deals with only the marketable goods and propose a new environmentally sustainable account system, in which the damage costs of pollutants and monetary cost of depletion of natural resources are subtracted from the national income. The optimum solution of the normative model refers to situations where more resources are reserved for future generations and less pollutants are discharged into the environment. It becomes clear that the performance of dynamic optimization of economic activities in the environmental account system is more profitable than that in conventional account system.

From the simulations, the authors obtain the following results:

1) In the case of the standard damage costs scenario, where the average of the observed damage costs due to discharge of air pollutants in developed nations is subtracted from the national income, minimum relative ratio of total world carbon emission is 77.4 % in 2040 compared with the reference scenario. Average throughout the 21st century is 84.0 %.

2) The standard damage costs scenario results in the decline of consumption level in developing countries much larger than in developed nations.

3) The high damage costs scenario is found to keep the carbon emission amount at the 1990 level up to the first half of the 21st century, and disadvantageously considerably large amounts bring twice the decrease of the consumption level in the standard damage costs scenario.

4) The low damage costs scenario does not bring so much decrease in consumption level, and only about 10 % reduction of carbon emission compared with the reference scenario.

5) "Net consumption" is defined as the consumption level minus the values of damage induced by pollutants. In examining the net consumption in the case of the standard damage costs scenario and the one in the reference scenario, the former net is larger at the beginning of 21st century. When the authors compare the differences of the sum of the discounted net consumption throughout the 21st century, the damage cost scenario has higher value than the reference scenario. These differences are more notable in the higher damage costs scenarios.

6) When introducing this new environmentally sustainable account system, discharged pollutant loads such as SO_x and NO_x are also reduced.

7) Since the society gives greater priority on the future generations in this sustainable system, the consumption of fossil fuels is managed to be reserved for the future generations. The depletion of reserved resources in each of the case of sustainable income scenarios is slower than in the case of the conventional economic system even with low economic growth rate.

8) Although afforestation program is not preferred under the conventional account system in the simulation, the new environmentally sustainable account system make afforestation to be preferably chosen. In this new account system with afforestation program, carbon reduction is realized more than in the situation without it. In the standard scenario with afforestation, 420 million tC/year more carbon can be reduced compared with the one without it.

9) In this new sustainable account system with afforestation, the average annual consumption level throughout the 21st century is maintained to 15.4 billion dollars more than the one without it, which is 0.021 % of the world consumption level, even when afforestation cost is subtracted from the national income.

10) Each group of countries receives different effects of afforestation. In developed nations, afforestation is regarded as the absorption of CO₂ in the late of 21st century. On the contrary, in developing countries, it has the effects of both absorption of CO₂ and supply of biomass energy throughout the 21st century.

From these results of simulations, the authors can conclude as follows. More pollutant reductions and wider afforestation actions become reasonable by introducing the income to account for the damage costs of pollutants, monetary costs of depletion of natural resources and so on. Moreover, when the damage costs of pollution or monetary costs of resource depletion become more expensive, the world could take net consumption much more than in the case of not regarding the damage costs and monetary costs of resource depletion throughout the 21st century.

Issues to be further investigated in the model simulation research are as follows:

(1) Damage costs are to be reasonably discounted in developing countries considering the overload on national economy with far less per capita production.

(2) Simulated results in medium temporal scale of one generation are examined. Dynamics in one century is based on the viewpoint that the long time horizons are considered in dealing with global environmental problems.

(3) It is desirable to modify the model structures for the purpose of analyzing the effects of the joint implementation. In this paper, all the costs of afforestation program are charged by the domestic regions. This joint implementation aims for developed nations to pay the cost of afforestation program and receive a part of the benefits or responsible share of mitigating global warming from afforestation.

(4) Sensitivity analyses of various parameters, especially energy supply and cost parameters, are required. In this paper, advantageous effects by introducing environmentally sustainable account are analyzed, but it does not ignore the economic effects of technology innovation. The reason of this is that the wise use of mixed energy attributable to the new account system is indebted to the technology innovation, especially in the field of carbon free backstop technology. It is necessary to analyze the efficiency of carbon elimination by technology innovation parameters.

(5) The constant removal ratio of pollutants is modified into parameters influenced by the magnitude of national economy, accumulated damage cost, and so on.

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