Measuring Weak Sustainability for the future: Calculating Genuine Saving with population change by an integrated assessment model

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Abstract

This paper presents a future figure of Genuine Saving with population growth (GSn). This was enabled by using an integrated assessment model, similar to the RICE model by Nordhaus. The model consists of sub-models that evaluate various kinds of mineral resources and environmental impacts. Results indicates that GSn is positive i) in OECD during the 21st century, ii) in World and the former Soviet Union and East Europe after 2030, and iii) in Asia and the Middle East and Africa after 2050. GSn is negative in Latin America during the 21st century.

Keywords : Genuine Saving, population change, sustainability, integrated assessment model, impact assessment model, growth model

JEL Classification: *Q01, Q56*

1. Introduction

Theoretical studies on growth theory and sustainability based on neo classical economics have been well developed. In a list of representative studies one might mention optimal saving [Ramsey 1928], utilitarian optimal growth [Koopmans 1960], the so called DSHH model which deals clearly with exhaustible resources [Dasgupta and Heal 1974/1979, Solow 1974, Stiglitz 1974], net investment [Dixit, Hammond, Hoel 1980], sustainability as a non declining utility [Pezzey 1989], sustainability criteria [Chichilnisky 1996], the dispute between WS and SS [Neumayer 2003], evaluation of natural capital and intra-generation equity [Dasgupta 2001], and inter-generation equity [Asheim 2008, Roemer and Suzumura 2009].

Compared with such theoretical and conceptual progress in economics, there are very few studies for sustainability in applied economics; by Peace, Atkinson, and Hamilton [Pearce and Atkinson 1993, Hamilton and Clemens 1999, Hamilton 2003/2006/2007]. Recent studies are by Arrow and Dasgupta based on those by Hamilton [Arrow and Dasgupta 2004, Dasgputa 2007]. This paper presents GSn for the future by applying IAM for assessing climate policy and energy technology assessment.

2. A brief explanation of data comparisons between this and existing studies

2.1. Existing study

The methodology to estimate GSn used in this study is the same as that in existing ones. However, the author believes that the consistency of data differs greatly. For example, Hamilton 2003 defines social welfare V as equation (1) by use of C as consumption, B as services from environment, ρ as a pure rate of time preference, $U(C,B)$ as utility.

$$V = \int_t^{\infty} U(C,B) e^{-\rho(s-t)} ds \to \max \quad \cdots \ (1)$$

Subject to $\dot{S} = -R + g(S)$, $\dot{X} = e - d(X)$, $\dot{N} = q(m)$, $\dot{K} = F(K,R,N) - C - a - m - \delta K$

Here, when we set stocks S, X, N, K as state variables, R, a, m, C as control variables, shadow prices of the stocks as γ_K, γ_S, γ_X, γ_N, a Hamiltonian function of this maximization model can be written as equation (2), where Genuine Saving without population change (GS) can be defined as equation (3).

$$H = U(C,B) + \gamma_K \dot{K} + \gamma_S \dot{S} + \gamma_X \dot{X} + \gamma_N \dot{N} = U + U_C \cdot GS \quad \cdots \ (2)$$

$$GS \equiv (GNP - C - \delta K) - n(R - g) - b(e - d) + \left(\frac{1/q'}{m/q} - 1 \right) m \quad \cdots \ (3)$$

Hamilton 2003 calculated GS by R as resources extraction, n as resource rental obtained by international price minus cost (mining, milling, concentrating, smelting, refining, transport, and rate of return of capital). b is willingness to pay to avoid environmental pollution. 20$/tC by Fankhauser's estimation of the social cost of carbon [Fankhauser 1998] is applied to the calculation. e is amount of pollution release (CO2 emissions). These n, R, e are obtained from a single data base (WDI [World Bank 2002]); however, the contents of which are gathered from varieties of statistical data, as listed in the references of Hamilton and Clemens 1999, for respective purposes. Hence, we cannot escape from the possible risk of inconsistency among the data used for estimating GSn.

2.2. This study

2.2.1. Macro economy parameters

The IAM approach can give data to estimate GSn from both exogenous and endogenous parameters of the IAM. Both exogenous and endogenous parameters are consistent since they all exist in optimal point. Exogenous parameters of IAM (named GRAPE/LIME [Kurosawa 1999, Itsubo 2005, Kosugi 2005, Kosugi 2009]) used in this study for GSn estimation are the following; future scenarios (population, demands of energy, mineral resources, and food), resource availability, cost data of processes (i.e., mining, milling, smelting/refining of non ferrous metals, steel production, cement production, power generation, and chemical conversions etc.), Dose-Response relation of environmental degradation, and willingness to pay to avoid damages. All the other data required for GSn estimation are all obtained endogenously from the model.

The model formulation (equation 4) is to maximize social welfare $V(t)$ equal to present value of discounted total welfare of the product utility and population, where $P(s)$ is population (exogenous), $C(s)$ is consumption (endogenous), utility function U is the logarithm of per capita consumption, ρ is a pure rate of time preference.

$$V(t)=\int_{s=t}^{\infty} P(s)\cdot\log\left(\frac{C(s)}{P(s)}\right)e^{-\rho(s-t)}ds \rightarrow \max \quad \cdots \ (4)$$

In the model, s is not time-continuous, but discrete with 10-year time steps (denote "yr" hereafter) from 2010 to 2150. The period after 2150 is added by using the sum of an infinite geometric series. The model divides the world into ten regions, which are North America, West Europe, Japan, Oceania, China, East-South Asia (including India), Mid-East and North Africa, Sub-Sahara Africa, Latin America, and the former Soviet Union and East Europe. For population, the scenario from the B2 storyline of the Special Report on Emissions Scenarios by the IPCC (Intergovernmental Panel on Climate Change) [IPCC 2000] is used as exogenous scenario $P_{rg,yr}$ by time step and world region.

In order to obtain consumption endogenously, the main body of the model consists of a sub model to express the macroeconomic relationship between things such as output, investment, capital stock depletion, GDP, intermediate inputs (supply cost of resources and land use), and external costs. The structure resembles that of the RICE model by Nordhaus [Nordhaus 2000]. These macroeconomic parameters can be obtained endogenously in the model.

2.2.2. Resource depletion and environmental degradation

Resource depletion related to GSn estimation can be obtained from a mineral resources sub model. The structure of the sub model is to minimize the discounted present total cost of mineral supply from mining to regional final resources demand with time-steps. Notation *m*, *rg*, and *yr* means resources, regions, and time-step, respectively. The following endogenous variables that are needed for the GSn calculation can be obtained by solving the sub-model.

amount of resource extraction $q_{m,rg,yr}$ and cumulative extraction $Q_{m,rg,yr}=\sum_{2010}^{yr} q_{m,rg,yr} \quad \cdots \ (5)$

marginal resource extraction cost $mxc_{m,rg,yr}$ (equals to dividing marginal cumulative extraction with marginal total extraction cost) $\cdots$(6)

marginal resource price $mp_{m,rg,yr}$ (equals to dividing marginal change of world resources trade balance with marginal resource quantity of import/export) $\cdots$(7)

resource rent $n_{m,rg,yr} = mp_{m,rg,yr} - mxc_{m,rg,yr}$ $\cdots$(8)

- m = oil, gas, coal, uranium, iron, bauxite, copper, lead, zinc, and limestone
- yr = 2010, 2020, …, 2150
- rg = North America (NAMR), West Europe (WEUR), Japan (JAPN), Oceania (OCEA), China (CPAS), East-South Asia including India (ESAS), Mid-East and North Africa (MENA), Sub-Sahara Africa (SSAF), Latin America (LAMR), and Former Soviet Union and East Europe (FSEE)

Environmental degradation for the GSn calculation can be obtained from the sub-model of environmental impact. The sub-model is originated from a lifecycle impact model, named LIME [Itsubo 2005], the so called Japanese version of Extern E [ExternE]. LIME, which can derive the external cost of various present day impacts in Japan, is modified to be compatible with the model framework of the original GRAPE. External costs can be calculated by equation (9). LIME provides *WF* and *DR* in the equation, which are exogenous variables.

$$DC_{rg,yr} = \sum_{sgo} WF_{sgo,rg,yr} \cdot \sum_{sbs} DR_{sgo,sbs,rg,yr} \cdot Inv_{sbs,rg,yr} \quad \cdots(9)$$

$$WF_{sgo,rg,yr} = WF_{sgo,JPN,yr_0} \cdot \left(\frac{GDP_{rg,yr} / P_{rg,yr}}{GDP_{JPN,yr_0} / P_{JPN,yr_0}} \right)^{\sigma} \cdots(10)$$

- sgo = safe guard object (human health, social capital, net primary production (NPP), biodiversity)
- sbs = greenhouse gases (GHG), ozone depletion substances (ODS), extraction and disposal of non fuel minerals, land use and land use change (LU&LUC)
- $WF_{sgo,JPN,yr_0} =$ marginal willingness to pay derived by conjoint analysis from a social survey of one thousand people in Japan, 2006.
- σ = elasticity of benefit transfer (0.5 is assumed from late David Pearce's review in 2003)
- $DR_{sgo,sbs,rg,yr} =$ Dose-Response relation from inventories release to safe guard objects (resembles to ExternE)
- $Inv_{sbs,rg,yr} =$ inventories treated in the model, such as CO2, SOx, NOx from fuel combustion, CO2 release via deforestation, five kinds of non CO2 GHG (NCGHG), fourteen kinds of ODS, extraction and disposal of non fuel minerals, LU&LUC. NCGHG and ODS are exogenous, all the others are endogenous.

3. Measuring Genuine Saving with population change for the future in this study

3.1. Genuine Saving（GS）without population change

This method, applied in Hamilton&Clemens 1999, Hamilton 2003/2006/2007, is to derive GS from the relation of $H = U + U_C \cdot GS$ in equation (2). This is an estimation of GS without population change. In this paper, GS can be calculated from equation 11 through use of numerical simulation outputs from the GRAPE/LIME model. All the terms in this equation can be obtained endogenously. Resource depletion is, as explained, ten kinds of fuel and non fuel minerals; $q_{m,rg,yr}$ is equation (5), $n_{m,rg,yr}$ is (8), and $DC_{rg,yr}$ is (9), respectively.

$$GS_{rg,yr} = GDP_{rg,yr} - C_{rg,yr} - \delta K_{rg,yr} - \sum_{m}\left(n_{m,rg,yr} \cdot q_{m,rg,yr}\right) - DC_{rg,yr} \quad \cdots (11)$$

3.2. Genuine Saving with population change（GSn）

The precise calculation of GSn is a hard problem (see [Arrow, Dasgupta, Maler 2003, Asheim 2004]). References [Hamilton2006/2007, Dasgupta 2001, Arrow and Dasgupta 2004] escape this problem by giving the following three assumptions to calculate GSn.

- Rate of population change is constant
- Per capital consumption is independent of size of population
- Production function is assumed to be a constant return to scale

These three expressions of GSn are mathematically identical: “rate of change of per capital wealth (equation 12)” in Hamilton 2003, “changes of per capital wealth equals to GS minus Malthusian term (equation 13)” in Hamilton 2006/2007, and “Genuine Investment (GI; equation 14)” in Dasgupta 2001.

$$w = \frac{d}{dt}\left(\frac{W}{P}\right) = \frac{W}{P}\left(\frac{\dot{W}}{W} - \frac{\dot{P}}{P}\right) = \frac{W}{P}\left(\frac{GS}{W} - p\right) \quad \cdots (12)$$

$$GSn = \frac{GS}{P} - p\frac{W}{P} \quad \cdots (13)$$

$$GI = \frac{\sum_{i} p_{it}\frac{dk_{it}}{dt}}{\sum_{i} p_{it}k_{it}} = \frac{I_t}{\beta_t Y_t} - p = \frac{I_t}{Y_t}\cdot\frac{1}{\beta_t} - p = \frac{GS}{Y_t}\cdot\frac{1}{\frac{W}{Y_t}} - p = \frac{GS}{W} - p \quad \cdots (14)$$

Here, as described in reference (Hamilton and Hartwick 2005, Hamilton 2007), *W* is the discounted sum of consumption from present to infinity, called Total Wealth (*TW*) in equation 15. GSn in this study is calculated as equation 16 in reference to these studies

$$TW_t = \int_{t}^{\infty} C(s)e^{-\rho(s-t)}ds \cdots (15)$$

$$GSn_{rg,yr} = \frac{GS_{rg,yr}}{P_{rg,yr}} - p_{rg,yr} \cdot \frac{TW_{rg,yr}}{P_{rg,yr}} \cdots (16)$$

3.3. Results

Figure 1 illustrates Gross Saving (upper side of solid line), Genuine Saving (lower line), and the difference between them (i.e., resource depletion and environmental degradation is indicated by the bar graph). The impact on LU&LUC, particularly on LU is apparent. This model based on LIME treats reduction of NPP by LU as damage, to the potential NPP at the location, which is accounted as an external cost. The second largest impact next to LU is depletion of energy resources.

One result of 2030 as an example is shown in Table 1, that GSn becomes negative when accounting for population change, although GS (without population growth) is positive. This table resembles that in Hamilton 2006 and indicates as follows, per capita GDP in the first row, population growth rate p in the second, first term of equation 13 in the third, second term except g in eq.13 in the fourth, eq.13 in the fifth, and, a number obtained by dividing the fifth column with the fourth column. Per capita GS of MENA (in the third row) is 438 \$/cap, which becomes - 203 \$/cap when population growth is counted. It is worth mentioning, however, that this is only four amongst all hundred cases (ten regions times ten time-steps).

Figure 2 presents the trajectories of both GS and GSn from 2010 to 2100, the horizontal axis indicates GS, while the vertical axis indicates GSn. Presenting all the data of ten world regions in the fifteen time-steps would make the data hard to understand, so we use data plots (indicated by markers in the figure) of six geographical points (ten regions are aggregated to five regions, plus global) in 2010, 2030, 2050, and 2100, to draw the trajectories.

Both GS and GSn are positive (hence satisfying the necessary condition for sustainability), during the 21st century in OECD (= NAMR, WEUR, JAPN, OCEA), after 2030 in FSEE and World, after 2050 in Mid East and Africa (= MENA plus SSAF), and Asia (= CPAS plus MENA); however, both are negative during the 21st century in Latin America, indicating unsustainability.

The above results are based on SRES-B2 scenario. Following result is based on both population and GDP scenario of SRES-B1. The distinct difference of these two scenarios is population change. Both of population scenarios are growing in the former half of the 21st century. The population growth rate of B1 is decreasing to halt in 2050, then to turn negative though that of B2 is still positive in the latter half of the century. Compared with B2, low population leads to low urban land area requirement, and to low both crop and grass land area due to low food demand. The low population also leads to low transportation energy demand, resulted in comparative CO2 emissions in 2100 to those in 2000 in B1 scenario. Moreover, GDP level in B1 is some 20 percent lower than B2 in the former half of the century, nearly equal in the latter half. Therefore, external cost of percent GDP of B1 compared with B2, is somewhat higher in the former half, then turn to lower in the latter half of the century.

Such inclinations are reflected in the results of both GS and GSn of the scenarios, shown in Table 2. The numbers of 1 and 2 in the table means scenarios of B1 and B2, respectively. DC, TW, and p means external cost, Total Wealth, population growth rate, respectively. We can understand that the main cause of the difference of GS (the forth row) is come from that of the external cost (the third row), and that relative change of external cost is also reflected to that of GS. The difference of the external cost plus that of population change leads to that of GSn since percent of TW is almost constant.

4. Summary

This paper presents the results of calculating Genuine Saving with consideration for population change (GSn) by applying a so called integrated assessment model (IAM) that is used in the field of climate policy assessment.

The following three points can be listed as the merits of this approach (hereafter "IAM approach") compared with an existing applied economic approach (hereafter "existing approach") carried out by Kirk Hamilton and Partha Dasgupta using varieties of statistical data. 1) The IAM approach can provide the future value of GSn, while the existing approach can only display GSn in the past. 2) The former can take into account elements of *future* scenarios such as climate policies, deployment of energy technologies, and the supply and demand of resources within the context of sustainability, while the latter can analyze policy outcomes in the *past*. 3) Both exogenous input data and endogenous output data of the IAM used for GSn calculation are consistent since they satisfy the optimal solution point. The latter approach cannot escape from possible inconsistencies in statistical data applied to the calculation.

The main structure of the IAM used in this study is orthodox in which utility is a logarithm of per capita consumption. An objective function of the model is inter-temporal maximization with time discount of total welfare which equals to a product of utility and population. The existing approach is first to make a similar formal model then derive analytic solutions, into which statistical data are substituted to calculate GSn. The IAM approach in this study derives formal settings to make a numerical calculation with discrete data divided into ten global regions and fifteen time steps from 2010 to 2150. The required data to calculate GSn, such as GDP, consumption, resource depletion (market resource rent and extraction), and environmental degradation (external cost of non market resources), can be endogenously obtained via an optimization procedure.

The version of the model used in this study deals with both the depletion of non fuel mineral resources and various environmental impacts via a resembling impact assessment model of Extern E, in order to reflect these things as much as possible for the GSn calculation. Subsoil resources dealt with in this model are fuel minerals (oil, gas, coal, uranium) and non-fuel minerals (iron, bauxite, copper, lead, zinc, limestone). This number of resource-types (ten) is a little less than those treated in studies by Hamilton (thirteen). Surface resources (on land, such as forest, timber, and foods etc.) are not yet included in this calculation. Environmental impacts include i) global warming, ii) depletion of the ozone layer, iii) acid rain, iv) local air pollution, v) impacts on both potential net primary production (NPP) and biodiversity via land use and land use change (LU&LUC), and vi) extraction and disposal of mineral resources. This study deals with the largest number of impacts among these kinds of models, although it cannot yet be considered necessary or sufficient for natural capital evaluation.

The model used for the GSn calculation is still in development, so the obtained results should be considered as tentative and in need of revision. GSn is positive i) in OECD during the 21st century, ii) in World and the former Soviet Union and East Europe after 2030, and iii) in Asia and the Middle East and Africa after 2050. GSn is negative in Latin America during the 21st century. Therefore, the necessary condition for sustainable development is satisfied in the regions of the time horizon with positive GSn. The deciding factor declining from Gross Saving to Genuine Saving is the external cost of reducing potential NPP via land use.

Since the main structure of the model is orthodox, inter temporal, time discounted utility maximization type, this study neither makes progress in the economic field of sustainability studies, nor does it escape from the inevitable essential failure that optimality is not always compatible with sustainability. Although such shortcomings are recognized, the author believes that this IAM approach has potential usefulness as an applied sustainability study in economics, a field in which theoretical study has been well progressed.

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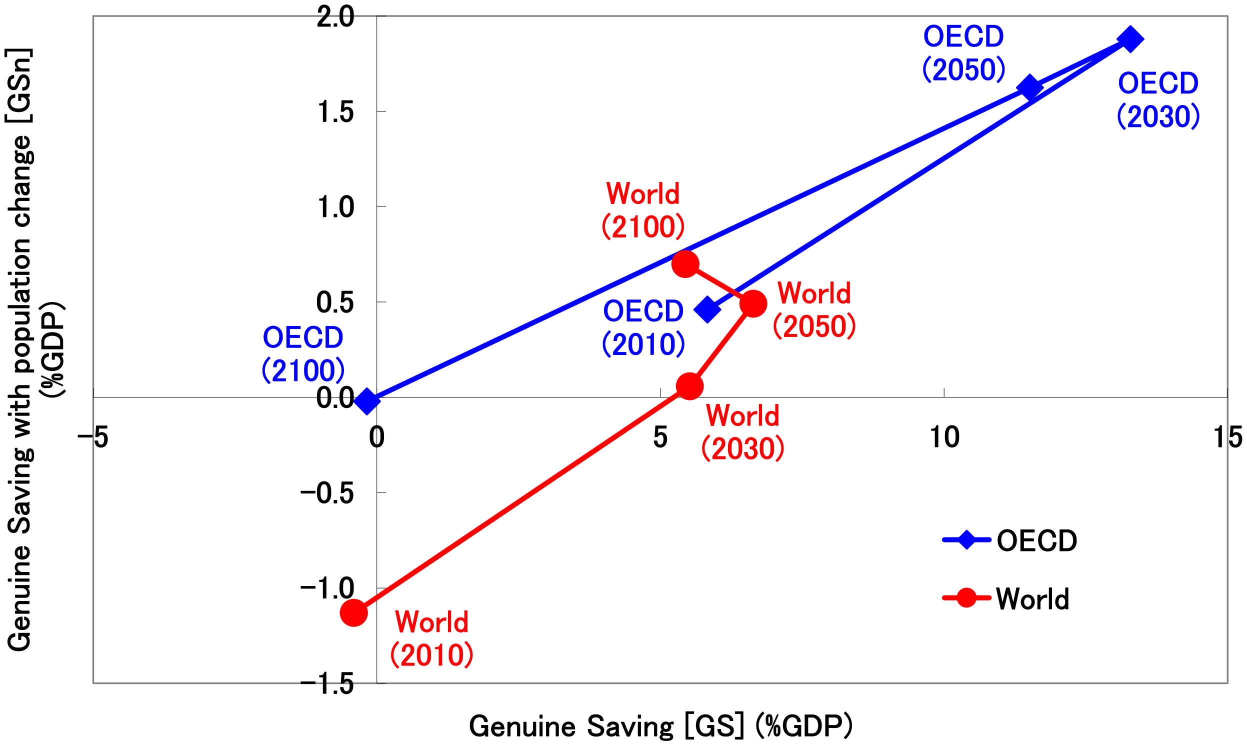
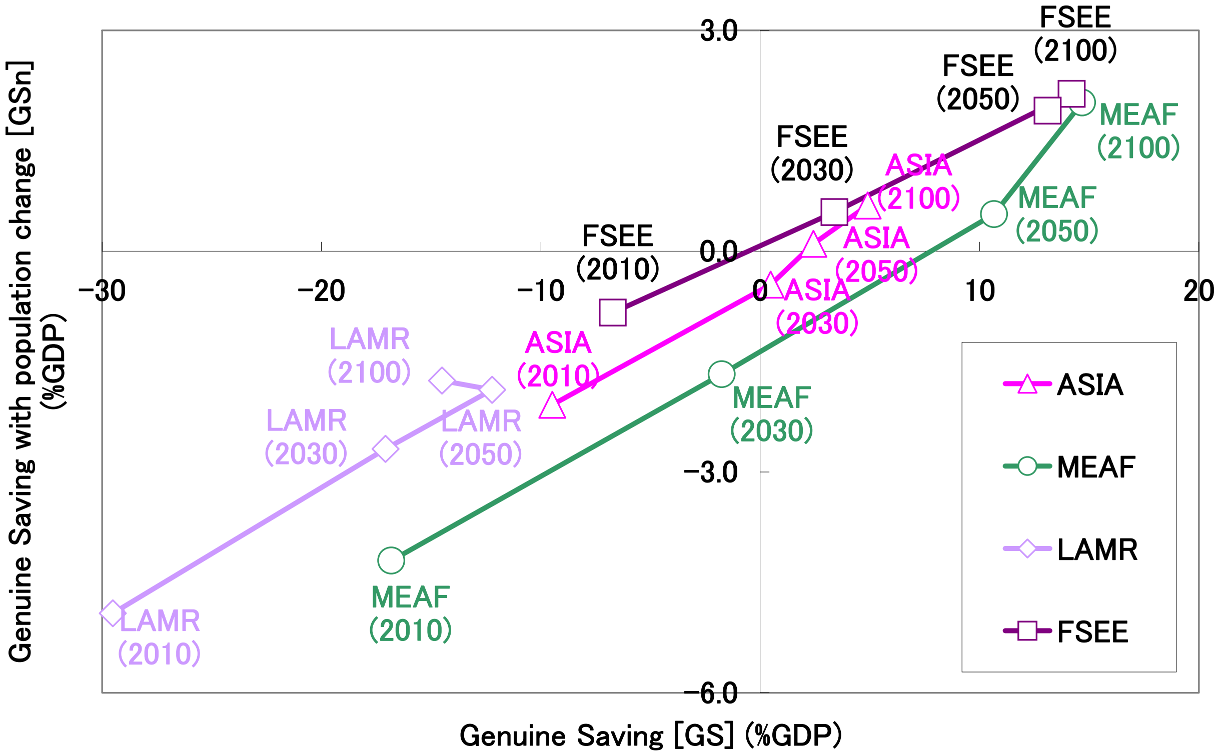


(a) World and OECD



(b) The Former Soviet Union and Eastern Europe (FSEE) and Developing Countries

Figure 1 Trajectories of GS and GSn in aggregated world six regions

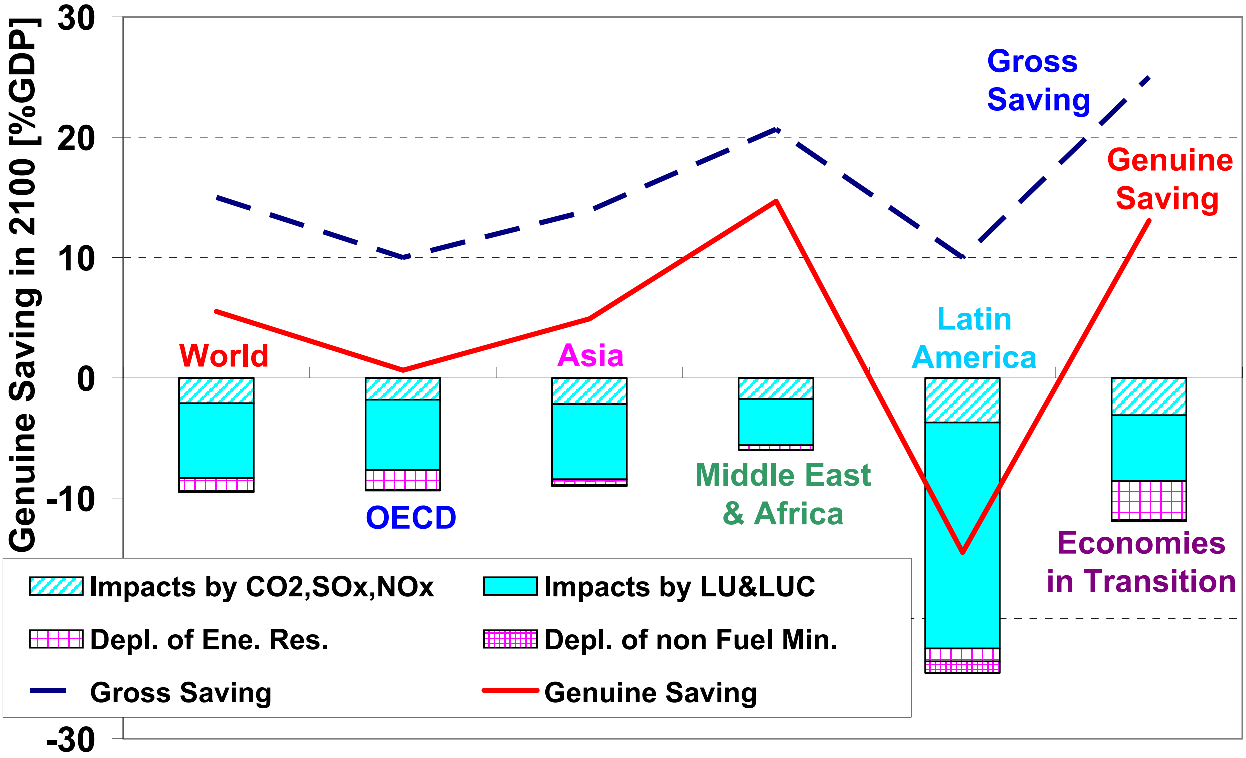


Figure 2 Difference between Gross Saving and Genuine Saving with its breakdown in 2100

Table 1 Comparison of GDP/cap, GS/cap, and GSn/cap in 2030

	GDP per catita ($/cap)	Population growth rate (%)	Genuine Saving per capita ($/cap)	Wealth per capita ($/cap)	Change in Wealth per capita ($/cap)	Change in Wealth (% of total)
NAMR	34,942	0.3	4,957	253,699	4,137	1.6
WEUR	36,860	−0.4	5,118	267,553	6,101	2.3
JAPN	40,526	−0.4	7,493	287,401	8,704	3.0
OCEA	34,936	0.3	−10,851	288,242	−11,768	−4.1
CPAS	7,600	0.0	267	62,796	241	0.4
SEAS	6,016	0.7	−91	49,705	−463	−0.9
MENA	6,904	1.1	438	57,040	−203	−0.4
SSAF	1,471	1.6	−318	12,190	−516	−4.2
LAMR	5,064	0.6	−865	41,899	−1,126	−2.7
FSEE	7,542	−0.1	255	62,425	331	0.5
TOTAL	9,287	0.6	513	72,446	42	0.1

Table 2 Comparison of results by SRES-B2 and by SRES-B1

	2010	2030	2050	2100	row number
DC1 [%GDP]	-17.3	-10.3	-9.4	-6.3	①
DC2 [%GDP]	-14.8	-9.3	-8.7	-8.3	②
DC1-DC2 [%GDP]	-2.5	-1.0	-0.6	2.0	③＝①－②
GS1-GS2 [%GDP]	-3.9	-4.1	-0.2	2.4	④
GS1/TW1-GS2/TW2 [%GDP]	-0.5	-0.5	0.0	0.3	⑤＝④/7.8
p2-p1 [%GDP]	0.1	0.2	0.4	1.0	⑥
GSn1-GSn2 [%GDP]	-0.4	-0.3	0.4	1.3	⑦＝⑤＋⑥

Appendix

A. A brief outline of an integrated assessment model : GRAPE/LIME

A.1. Model framework and inter-linkages of sub-models

The model framework of the GRAPE/LIME is made by hard linkages among sub-models of macro-economy, energy, land-use, climate (those four are from the original GRAPE model [Kurosawa 1999]), environmental impacts modified from LIME [Itsubo], and originally developed non-fuel minerals (Appendix Figure 1). The sub-model of non-fuel minerals deals with mineral extraction, via the floating, refining, smelting, and producing of final products, to recycling and disposing. These processes are linked to a sub-model of energy to calculate energy consumption endogenously, as well as to a sub-model of impact assessment (LIME) to calculate the external cost of land use change via the degradation of copper, lead, and zinc due to the extraction and waste disposal of all mineral resources. External costs are also calculated in the impact assessment sub-model for global warming, acidification by acid rain, and air pollution by CO2, SOx, NOx from the energy sub-model; for global warming by CO2 release due to deforestation, and for damage to both NPP and biodiversity by LU&LUC in the land-use sub-model. These internal costs and external costs are linked to the macro-economy sub-model.

A.2. Objective function

The object function is expressed as a discrete equation (A1), where $C_{rg,2150}$ is consumption at 2150, $c_{rg,yr} = C_{rg,yr} / P_{rg,yr}$ is regional per capital consumption, $\dot{c}_{rg}$ is annual growth rate of consumption from 2000 to 2150, Neg_{rg} is Negishi weight, and ρ is pure rate of time preference. The endogenous parameter of $C_{rg,yr}$ can be obtained via an optimization procedure.

$$V(2010) = \sum_{rg} Neg_{rg} \cdot \left(\sum_{yr=2010}^{2150} \left(\frac{1}{1+\rho} \right)^{yr-2010} \cdot P_{rg,yr} \cdot \log\left(\frac{C_{rg,yr}}{P_{rg,yr}} \right) + \sum_{yr=2150}^{\infty} \left(\frac{1}{1+\rho} \right)^{yr-2010} \cdot C_{rg,2150} \cdot \left(\frac{1+\dot{c}_{rg}}{1+\left(\rho+\dot{c}_{rg}\right)} \right)^{yr-2150} \right)$$

$$= \sum_{rg} Neg_{rg} \cdot \left(\sum_{yr=2010}^{2150} \left(\frac{1}{1+\rho} \right)^{yr-2010} \cdot P_{rg,yr} \cdot \log\left(\frac{C_{rg,yr}}{P_{rg,yr}} \right) + \left(\frac{1}{1+\rho} \right)^{2150-2010} \cdot C_{rg,2150} \cdot \left(\frac{1+\rho+\dot{c}_{rg}}{\rho} \right) \right) \to \max \cdots \text{(A1)}$$

A.3. A macro-economy sub-model

The following formulas relate macro economic parameters such as $C_{rg,yr}$, $I_{rg,yr}$, $Y_{rg,yr} = GDP_{rg,yr}$, and $F_{rg,yr}(K,L,E,M,LU)$.

$$C_{rg,yr} = Y_{rg,yr} - I_{rg,yr} + IM_{rg,yr} - XP_{rg,yr} \cdots \text{(A2)}$$

$$Y_{rg,yr} = A_{rg,yr} \cdot F_{rg,yr}\left(K,L,E,M,LU\right) - EMC_{rg,yr} - LUC_{rg,yr} - DC_{rg,yr} \cdots \text{(A3)}$$

$K_{rg,yr+1} = \left(1-\delta\right)^{10} \cdot K_{rg,yr} + I_{rg,yr}$ where δ is depletion rate of capital stock$\cdots$(A4)

The production function of the GRAPE/LIME, shown in (A5), is constructed as the following nested type; [KLEM and $LU_{rg,yr}$] and [KL and EM] are CES (Constant Elasticity Substitution); [$K_{rg,yr}$ and $L_{rg,yr}$], [$E_{rg,yr}$ (= $EL_{rg,yr}$ and $NE_{rg,yr}$) and $M_{rg,yr}$ (= $\sum_{nfm}\sum_{\sec} SP_{nfm,rg,yr} \cdot MD_{\sec,nfm,rg,yr}$ which is the product sum of the shadow price $SP_{nfm,rg,yr}$ and demand $MD_{\sec,nfm,rg,yr}$ of non fuel mineral resources)], and [$EL_{rg,yr}$ (electricity demand) and $NE_{rg,yr}$ (non electric energy demand equals of heat and liquid)] are a Cobb-Douglas production function.

- m = mineral resources (fm; fuel minerals, nfm; non-fuel minerals)
- sec = three manufacturing sectors (electricity and machinery, construction and building, motor cycles)

$$F_{rg,yr}\left(K,L,E,M,LU\right) = \left[\left[\left\{a_1\left(K_{rg,yr}{}^{\alpha} L_{rg,yr}{}^{1-\alpha}\right)^{-\varepsilon} + a_2\left(\left(EL_{rg,yr}{}^{\beta} \cdot NE_{rg,yr}{}^{1-\beta}\right)^{\gamma} \cdot M_{rg,yr}{}^{1-\gamma}\right)^{-\varepsilon}\right\}^{-\frac{1}{\varepsilon}}\right]^{-\lambda} + a_3 \cdot LU_{rg,yr}{}^{-\lambda}\right]^{-\frac{1}{\lambda}} \cdots \text{(A5)}$$

a1、a2、a3、 α 、 β 、 γ 、 ε 、 λ : parameters

$A_{rg,yr}$ is the calibration term indicated in equation (A6), between $F_{rg,yr}\left(K,L,E,M,LU\right)$ and the sum of intermediate input costs ($EMC_{rg,yr} + LUC_{rg,yr} + DC_{rg,yr}$) plus value added ($refGDP_{rg,yr}$) which is the benchmark GDP of SRES-B2 scenario of IPCC.

$$A_{rg,yr} = \frac{refGDP_{rg,yr} + EMC_{rg,yr} + LUC_{rg,yr}}{F_{rg,yr}\left(K,L,E,M,LU\right)} \cdots \text{(A6)}$$

$A_{rg,yr}$ can be endogenously obtained by equation A6 in a “Business As Usual (BAU)” case. When another case run is carried out, the endogenously obtained $A_{rg,yr}$ is given as an exogenous parameter in equation A3. $EMC_{rg,yr}$, $LUC_{rg,yr}$, $DC_{rg,yr}$ are (fuel and non-fuel) mineral supply cost, land use cost for food supply, and damage cost, respectively, each of which are explained in the following sections.

A.4. A sub-model of mineral resources: a demand - supply for energy (fuel) and non fuel mineral resources

The sub-model of mineral resources treats fuel minerals (fm; oil, gas, coal, uranium) and non-fuel mineral resources (nfm; iron, bauxite, copper, lead, zinc, limestone). This is a demand and supply model, in which supply deals with mining, milling, dressing, smelting and refining for nfm, the conversion process of either electrical or chemical for energy, transportation among the ten global regions, to the final demand of both energy ($EL_{rg,yr}$ and $NE_{rg,yr}$) and materials ($MD_{\sec,nfm,rg,yr}$) by three representative manufacturing sectors (electricity and machinery, construction and building, motor cycles). The nfm exist as in-use stocks of product goods during the assumed products lifetime, after which they become out of use stocks, and then are finally disposed or recycled.

A.5. A land-use sub-model

The land-use sub-model calculates the endogenous five categories of land use (lu; forestry, grass land, crop land, urban, others) and twenty kinds of land use change among the categories (= five times four), by satisfying exogenous demand for food and area of urban land (i.e., land area requirement for human settlement), by use of exogenous costs of land rent, land conversion, and food production.

The food demands are expressed as both calorie base and protein base, which are satisfied by crop productions in crop land and by meat productions in grass land. Each production is converted by use of yield to area of crop land and grass land (pasture land). The area of urban land is calculated from population and population density. Forest area is calculated via i) deforestation and reforestation due to carbon release and absorption, ii) conversion to crop land and grass land for food production requirements. The land category of “other” includes all others including such terrains as desert and reservation land, whose area will be kept constant. In short, the land area of “others” is constant, urban area is decided by population and population density, forestry is driven by food demand and global warming constraints, and both grass land and crop land satisfy aggregated food demand.

A.6. An impact sub-model (LIME)

The original LIME can treat eleven kinds of impact category. Six of them are included in GRAPE/LIME, which are global warming, ozone depletion, acidification, local pollution, LU&LUC, and extraction/disposal of non fuel minerals. The impact categories, explained in Appendix B, are related to four safe guard objects such as human health, social capital, net primary production, and biodiversity, by use of Dose-Response ($DR_{sgo,sbs,rg,yr}$) relationship like ExternE, then to single aggregated index (monetary term) of marginal willingness to pay (MWTP) by using conjoint analysis. The MWTP is derived by a social survey of one thousand people throughout Japan in 2006. The obtained value is transferred to other regions or future time steps by using unit benefit transfer with income adjustment (income elasticity of 0.5 from late David Pearce’s review in 2003).

The Dose-Response relations in Japan are indicated in LIME, which is adjusted to all regions and time-steps to suit GRAPE/LIME. The differences in region and time compared to present-day Japan are reflected by using a zero order approximation that considers the damage and impact to safe guard objects. To be specific, the ratio (between the value in a region in a time step as numerator and the value of the present-day as a denominator) is multiplied to values of Dose-Response in present-day Japan. The ratio of population density ratio for human health, per capita GDP for social capital, potential NPP for NPP, and the extinction risk of vascular plants for biodiversity, are applied to the multiplication.

B. Impact categories treated in GRAPE/LIME

B.1. Global warming

In order to develop damage functions for the safeguard subjects of human health (Itaoka et al., 2002) and social welfare (Uchida et al., 2002), (1) damage due to the impact pathway at the time of doubled CO_2 concentration was estimated as a benchmark, while global mean temperature was projected using the DICE model (Nordhaus, 1994); (2) time series impacts were estimated by interpolation and extrapolation based on the benchmark impacts considering regional population change (United Nations, 2003) and economic development (Nakićenović et al., 1998); (3) the damages were aggregated to estimate impacts per GHG emission.

B.1.1. *Damages for human health*

For thermal/cold stress, a dose-response coefficient between daily maximum temperature and mortality was expressed as a function of regional GDP per capita and annual average air temperature, applying a Japanese coefficient as the reference coefficient (Honda et al., 1998). For malaria, the population in malarial risk areas with and without climate change as simulated by Matsuoka and Kai (1995) was used to estimate the rate of population increase at malaria risk per 1 ^{o}C temperature rise. The increase rate of dengue risk due to temperature increase is assumed to be double that of malaria, as based on the study of Martens et al. (1997) who estimated that the rate of increase in the endemic potential for dengue due to temperature increase was 2.2 times that for malaria. For natural disasters, LIME referred to the expert judgments applied by ExternE (European Commission, 1999) that determined that damages by typhoons would increase by 25% and damages by other natural disasters would increase by 10% at the time of a 2.5 ^{o}C increase in global mean temperature. The increase in the number of people at risk of hunger due to temperature increase was estimated based on the report by Parry et al. (1999).

B.1.2. *Damages for social capital stock*

Future crop production up to the point of doubled CO_2 concentration, not considering a CO_2 fertilization effect, was calculated using the model of potential crop productivity developed by Kyoto University and the National Institute of Environmental Studies, Japan (Takahashi et al., 1997). In addition, the CO_2 fertilization effect was calculated based on the study by Cure and Acock (1986). To estimate the change in energy consumption for heating and cooling resulting from global warming, future heating and cooling degree days were calculated and the interaction between economic growth and heating and cooling energy consumption was analyzed using empirical energy consumption data for Japan (EDMC/IEE, 2002). The land elevation dataset ETOPO5 accessible via GRID-Tsukuba, originally developed by the NOAA National Geophysical Data Center (NGDC), was used to calculate the areas of submergence in the case of a 0.5 meter sea-level rise that plausibly corresponds to a doubled CO_2 concentration in 2100.

B.2. Land use

The increment of extinction risk of vascular species and the decrement of net primary production (NPP) of vegetation, as indicators of biodiversity and primary productivity, respectively, were assessed as damage indicators (Nakagawa et al., 2002). These damages were considered to be incurred by land use (land occupation) and land-use change (land transformation).

B.2.1. Damages to biodiversity

The extinction risk as employed in LIME is defined as the inverse number of the average years from the present until the extinction of a threatened vascular plant, originally based on the idea of extinction probability. A statistical model developed by Matsuda (Matsuda, 2000; Matsuda et al., 2003) based on the Red Data Book (RDB) in Japan (Environment Agency of Japan, 2000) was applied to estimate extinction probability. The damage factor corresponding to the location of land use was established by assessing regional biodiversity using the distribution of the RDB public species, which is called the hot spot map, accessible via the Internet from the Biodiversity Center of Japan.

B.2.2. Damages to primary productivity

NPP loss due to land use was derived by subtracting the actual NPP from the potential NPP, whereas that due to land-use change was assessed in terms of the potential decrease of NPP based on when the former area of land use would be recovered, taking into account the time necessary for recovering an area's potential. The recovery time was set according to the results reported by Numata (1987). The Chikugo model (Uchijima and Seino, 1985) including climatic data was applied to the calculation of the potential NPP. The field-surveyed NPP data compiled by Iwaki (1981) was utilized for the actual NPP.

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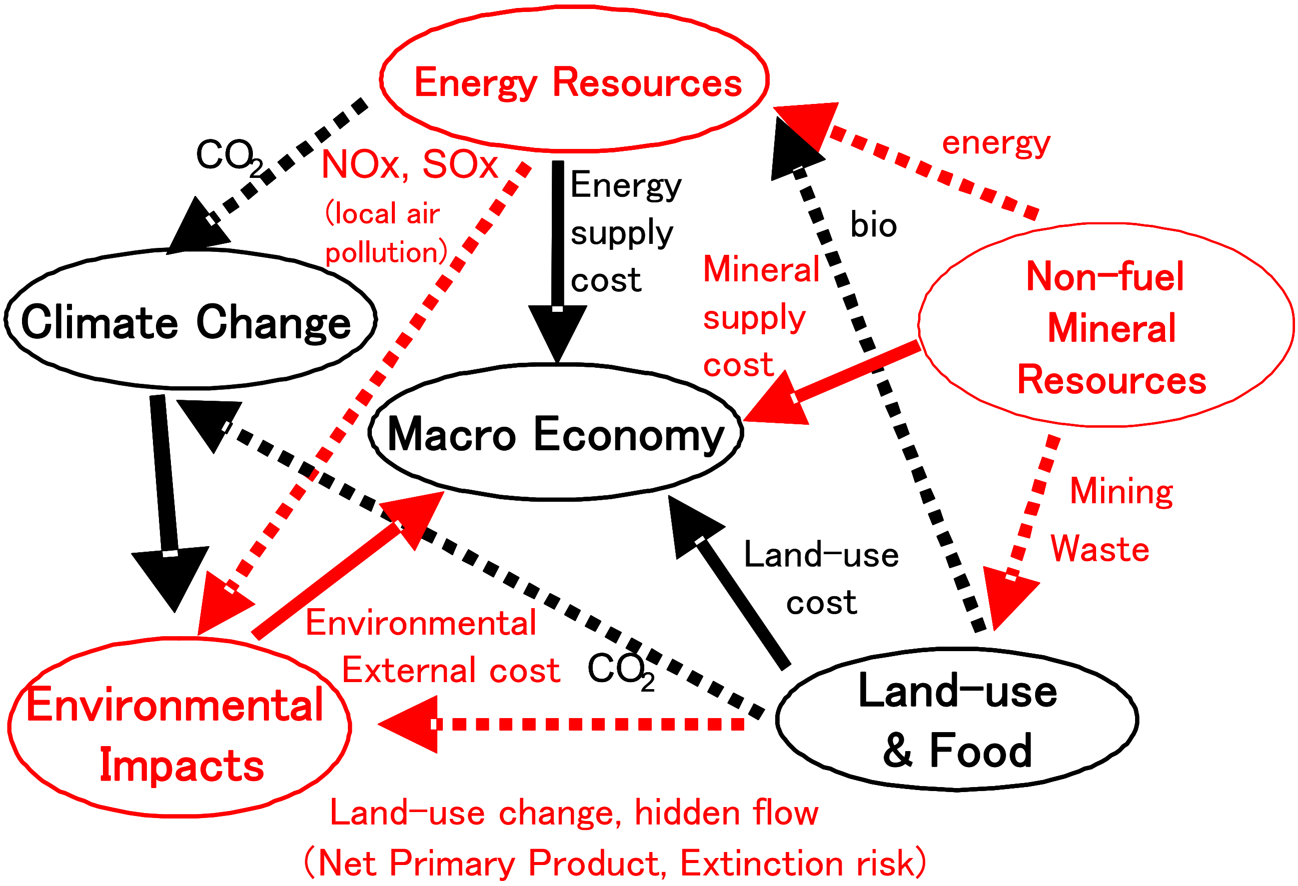
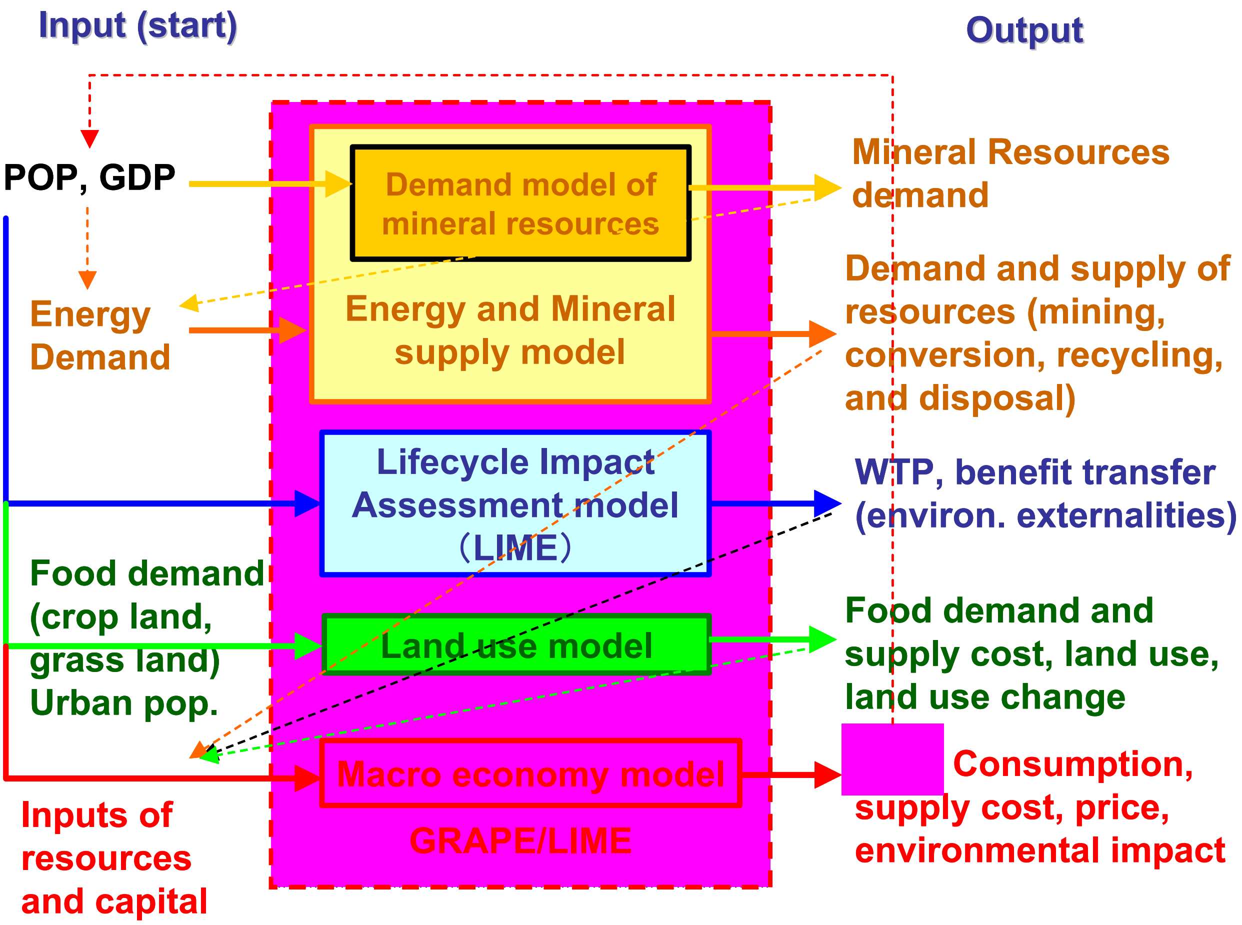
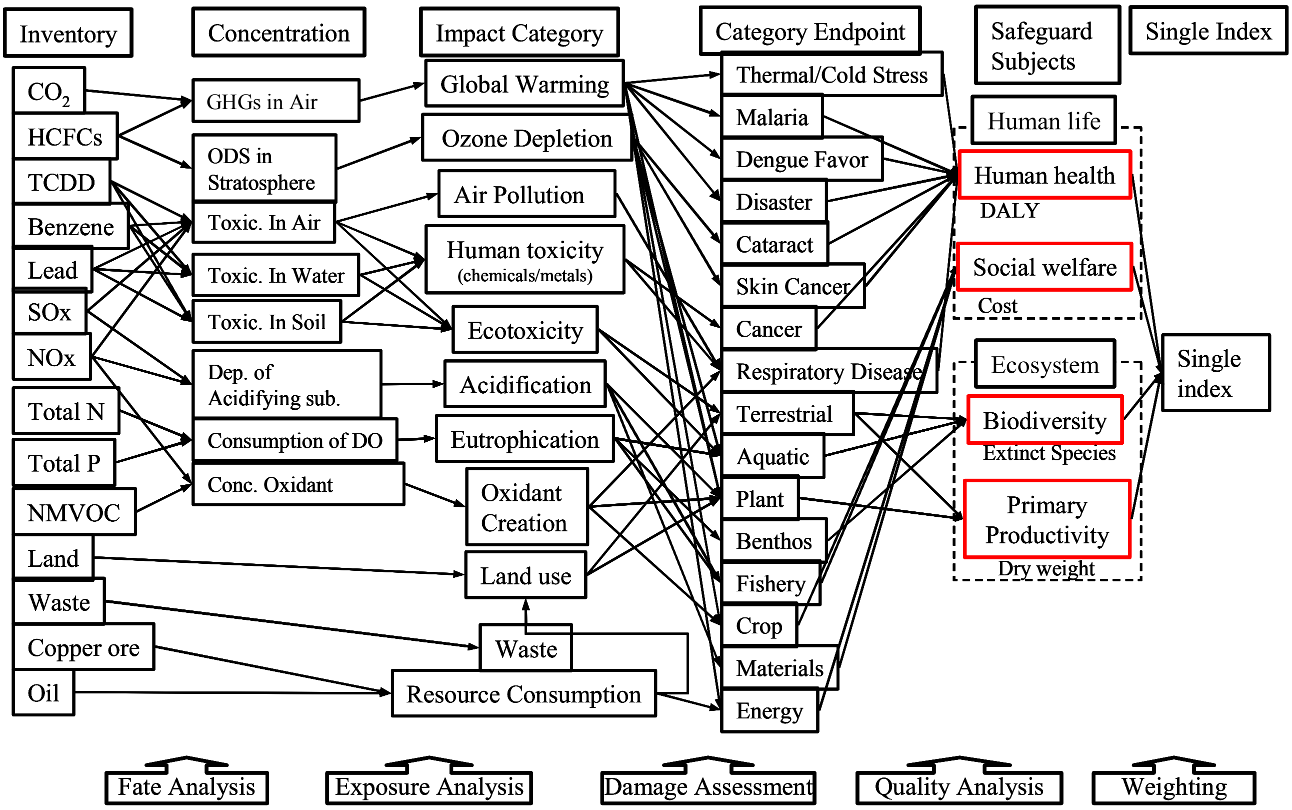


Appendix Figure 1 Framework and inter-linkages of sub-models of the GRAPE/LIME model



Appendix Figure 2　Data-linkages among sub-models of the GRAPE/LIME model



Appendix Figure 3　The framework of the LIME model

Appendix Table 1

Category endpoints considered in LIME in relation to impact categories and safeguard subjects

	Safeguard subject			
Impact category	Human health	Social welfare	Biodiversity	Primary productivity
Global warming	Thermal/cold stress, Malaria, Dengue, Natural disaster, Hunger (Itaoka et al., 2002)	Crop production, Land submergence, Energy consumption (Uchida et al., 2002)		
Ozone Depletion	Skin cancer, Cataract (Hayashi et al., 2002)	Crop&timber production (Hayashi et al., 2002)		Terrestrial plants, Phyto-plankton (Hayashi et al., 2002)
Acidification	(assessed in Urban air pollution)	Timber production, Fishery (Hayashi et al., 2000)		Terrestrial plants (Hayashi et al., 2004)
Photochemical oxidant	Respiratory disease, etc. (Nagata et al., 2002)	Crop&timber production (Nagata et al., 2002)		Terrestrial plants (Nagata et al., 2002)
Urban air Pollution	Respiratory disease, etc. (Nagata et al., 2002)			
Toxic chemical Substances	Cancer, Respiratory disease (Sakao et al., 2002)		(assessed in Ecotoxicity)	
Ecotoxicity			Extinction of vascular plants& aquatic life (Sakao et al., 2002)	
Eutrophication		Fishery (Hirosaki et al., 2002)		
Land use			Extinction of vascular plants (Nakagawa et al., 2002)	Terrestrial plants (Nakagawa et al., 2002)
Resource Consumption			Extinction of vascular plants (Ii et al., 2002)	Terrestrial plants (Ii et al., 2002)
Waste	(toxic impacts are considered in Toxic chemical substances)		Extinction of vascular plants (Ii et al., 2002)	Terrestrial plants (Ii et al., 2002)