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Measuring sustainable development for the future with climate change mitigation; a case study of applying an integrated assessment model under IPCC SRES scenarios

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Abstract The Intergovernmental Panel on Climate Change (IPCC) described mainstreaming climate change mitigation into development choices in its Fourth Assessment Report, chapter 12 of Working Group III. It also pointed out that “few macro-indicators include measures of progress with respect to climate change” despite the needs for the inclusion. This paper tackled this point in the following ways by applying an integrated assessment model. First, this study applied shadow prices and production, endogenously obtained from the model, instead of using market prices and statistical data used in preceding studies in the economics literature. Second, this study measured forecasts of genuine saving (GS) and wealth globally up to the year 2100, while preceding studies were constrained to past and current savings and wealth. Third, this study examined changes in GS and wealth in different future scenarios on IPCC SRES (Special Report on Emissions Scenarios) with CO_2 emissions constraints. Finally, the authors adopted a GS estimation methodology of shadow prices in imperfect economies by Kenneth Arrow and Partha Dasgupta, instead of that of perfect economies by Kirk Hamilton et al., on which the authors had based previous studies. This makes the indicator consistent with changes of wealth.

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JEL Classification Q01 · Q56

1 Introduction and objectives

Economics have long investigated the idea of wealth leading to sustainable development (SD), based on conceptual and theoretical economic backgrounds from its origin (Simpson et al. 2005). It has become clear since Weitzman (1976) that net national product (NNP) has a theoretical and an economic implication as an indicator of welfare in green GDP theoretical studies. Recent theoretical studies have clarified that genuine saving (GS) or genuine investments (GI) that are changes of wealth can theoretically express the concept of sustainable development (e.g., Pearce and Atkinson 1993; Dasgupta 2001; Pezzey and Toman 2002; Arrow et al. 2003; Asheim 2004; Dasgupta 2009).

Compared with such theoretical and conceptual progress in economics, there are relatively few studies for empirical analysis of the economics of sustainability; by Peace, Atkinson, and Hamilton (Pearce and Atkinson 1993; Hamilton and Atkinson 1996; Hamilton and Clemens 1999; Hamilton 2003; Hamilton and Atkinson 2006; World Bank 2006; Atkinson et al. 2007). These papers propose concept of GS with illustrative results, and expanding the measurement to inclusion of population dynamics, capital assessment, and wealth accounting, for all over the world in the past fifty years.

Recently, the number of studies is growing (Dasgupta 2001; Arrow et al. 2004; Arrow et al. 2007; Arrow et al. 2010; Ferreira and Moro 2011; Mota et al. 2010; Ollivier and Giraud 2011), which are extended from those by Peace, Atkinson, and Hamilton. However, the data applied so far to measure GS and wealth are market prices and statistical national accounts, which may have caused a significant gap between empirical studies and theoretical investigations.

Unarguably, one of the biggest concerns in the real world centered around the concept of SD is climate change, which makes it interesting to look at how the Intergovernmental Panel on Climate Change (IPCC) evolved its discussion on SD in the context of climate change since its First Assessment Report (FAR) that focused on the technology and cost-effectiveness of mitigation activities. The Second Assessment Report (SAR) included issues related to equity. The Third Assessment Report (TAR) noted the three broad classes of analyses or perspectives: efficiency and cost-effectiveness; equity and sustainable development; and global sustainability and societal learning. Chapter 12 of Working Group III in Fourth Assessment Report (AR4) Metz et al. (2007) explored ways to make development more sustainable by mainstreaming climate change mitigation into development choices. The chapter also reviewed several macro-indicators of SD mentioned above and pointed out that (1) few of them take climate change mitigation directly into consideration, and that (2) inclusion of this aspect in the use of macro-indicators is identified as an important area of research.

The current study advanced preceding studies and incorporated the two research fields (i.e., economics of sustainability and climate change mitigation) in the following manner. First, this study applied shadow prices (Bulckaen and Stampini 2009; Tokimatsu et al. 2011) and production endogenously obtained from an integrated assessment model developed originally, instead of using market prices and statistical data from preceding studies. Second, this study measured future global sustainable development up to the year 2100, while preceding studies could only measure past and current global sustainable development. Third, this study estimated the differences of GS and wealth at a future point under IPCC SRES scenarios (Nakićenović and Swart 2000). Finally, the authors adopted a GS estimation methodology by Kenneth Arrow and Partha Dasgupta in 2007 and 2010 that makes the measurement more consistent with the theory that pertains to GS as a change of wealth.

2 Method

2.1 Existing studies

Arrow et al. (2007) also estimated the wealth growth rate in 1995 and 2000 in terms of natural, physical, and human capitals. Specifically, they used the following procedure: (1) calculate the amount of stock and its changes in these three capitals in 1995 and 2000; (2) estimate the value of the capital stocks by multiplying these changes by accounting prices in 1995. The market prices were used to calculate the values for physical and natural resources, and the wage level for human capital; (3) subtract the net capital gain of oil and global warming damages from the values of these capital stocks; (4) calculate the ratio by dividing this subtracted value from the amount of total stock in 1995; (5) convert the ratio into annual changes; and (6) compute the changes in wealth by adjusting the rates of both the population growth and technological change.

2.2 This study

2.2.1 Outline

Difficulty in obtaining the shadow prices of each capital stock prevented us from computing GS. In this study, we computed GS using changes of each capital stock shown in Eq. (1). The three capital stocks, namely natural, physical, and human, are included in the equation. The values of these capital stocks are expressed as W_N, W_P, and W_H, respectively.

$$\overline{GS} = \frac{\mathrm{d}W_N}{\mathrm{d}t} + \frac{\mathrm{d}W_P}{\mathrm{d}t} + \frac{\mathrm{d}W_H}{\mathrm{d}t} \tag{1}$$

For the market goods of the natural and physical capitals, we followed the idea of Kunte et al. (1998); their stock values are equivalent to the sum of net present flow value of their infinite stream. This means that the sum of net present flow value generated by market goods can be considered to be capital stock value. For human capital, it is assumed to be possible to measure it from the education level of the labor force. We hence computed their stock value by multiplying the products of value of the exponential function in productivity improvement, value of the exponential function in human health, and labor population, by the shadow price of the value.

The model we used in this study (Tokimatsu et al. 2011), having the time horizon up until 2150 and using ten regional allocations globally,[1] enables us to treat various resources, environmental impacts, and related external costs. The resources are mineral resources, such as fuel minerals and non-fuel minerals. The impacts are global warming, local air pollution, acidification, ozone layer depletion, mineral extraction and disposal, and land use and its changes.

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[1] $yr = 2010, 2020, \ldots, 2140, 2150$, $rg =$ North America, Western Europe, Japan, Oceania, China, South and East Asia including India, Middle East and North Africa, Sub-Saharan Africa, Latin America, and the former Soviet Union and Eastern Europe.

In the model used in this study, the market goods of the natural and physical capitals (three industrial sectors of the final demands,[2] mineral resources,[3] wood,[4] foods[5]) were computed as the sum of net present flow value of the infinite stream of the multiplication of the amount of products (e.g., concentrates, bullion, and final products). Their rent was obtained by subtracting the marginal costs of their extraction, smelting, energy conversion, and final product manufacture, from the international trading price (shadow price of the balance equation of concentrates, bullion, final products of export and import).[6]).

The external cost was applied to the flow value of environmental impact (DC), for global warming, air pollution, acidification, ozone depletion, land use, and resource extraction and disposal. In this study, based on Arrow et al. (2007), we subtracted these external costs of the environmental impact (which is accounted for as flow value) from the changes of wealth (Eq. 2).[7]

$$\mathrm{GS} = \frac{\mathrm{d}W_N}{\mathrm{d}t} + \frac{\mathrm{d}W_P}{\mathrm{d}t} + \frac{\mathrm{d}W_H}{\mathrm{d}t} - DC \qquad (2)$$

Tables 1 and 2 show the computing framework used in this study. The ultimate goal is to compute $GS_{rg,yr}$, which is in the right bottom of Table 1, and $\mathrm{GS}_{n_{rg,yr}}$, $\mathrm{GS}_{nt_{rg,yr}}$ in Table 2. In the following section, computing methods are described for $W_{N_{rg,yr}}$, $W_{P_{rg,yr}}$, $W_{H_{rg,yr}}$, $\mathrm{DC}_{rg,yr}$, $n_{rg,yr}$, $\tau_{rg,yr}$ in the tables.

2.2.2 Estimation of the value of each capital stock

2.2.2.1 Value of the natural capital stock W_N We assumed that, according to Kunte et al. (1998), the value of the natural capital stock W_N is composed of the value of the capital stock derived from both subsurface mineral resources W_{Nm} and yields from surface (land) W_{Nbio}. W_{Nm} is computed from the sum of the net present flow value, which corresponds to multiply to the multiplication of extracted mineral resources $q_{mr,rg,yr}$ in quantity by the current value rent $nr_{mr,rg,yr}$ (Eq. 3). The rent is obtained by subtracting the marginal extract cost from the shadow price of the resources. The shadow price ($\partial X/\partial M$) is the marginal change of social welfare against the marginal change in trade balance in the quantity of concentrates and bullion ($\partial V/\partial M$), divided by the marginal change in social welfare against the marginal change in trade balance in monetary value ($\partial V/\partial X$). $r_{rg,yr}$ denotes the consumption discount rate, where $r_{rg,yr} = \rho + MUC \cdot g_{rg,yr}$, ρ is the pure rate of time preference and MUC is the elasticity of the marginal utility of consumption, simply set at unity.

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[2] Electric machinery products, automobiles, civil engineering and construction (*sec*).

[3] Mineral resources (*mr*) are composed of fuel mineral resources (*fm*) (coal, oil, gas, uranium) and non-fuel resources (*nfm*) (iron ore, bauxite, copper, lead, zinc, limestone).

[4] Logs, wood pulp, timber/boards, papers (*pw*).

[5] Pork, chicken, mutton, beef, rice, wheat, corn (*fd*).

[6] This is computed as follows: the marginal change of social welfare (total net value of utility) V against the marginal change of the import/export amount M ($\partial V/\partial M$) divided by the marginal change of social welfare (total net value of utility) V against the marginal change of import/export cost ($\partial X/\partial M$).

[7] The environmental impact, which is a non-market asset, could cause damage to the four endpoints (health of human beings, social assets, primary productivity, bio-diversity). Therefore, it is possible to include the primary productivity and biological diversity into the national capital, social assets into physical capital, and health of human beings into human capital, and subtract them as capital depreciation. However, this idea requires further examination.

Table 1 Computing framework in this study (*before* adjusting rates of population growth and technological change)

	Natural capital	Physical capital	Human capital	Environmental impacts	Summation
Current time step (yr) [Trill US$]	$W_{N_{rg,yr}}$ 2.2.2.1, Eq. (5)	$W_{P_{rg,yr}}$ 2.2.2.2, Eq. (6)	$W_{H_{rg,yr}}$ 2.2.2.3, Eq. (8)	–	$W_{N_{rg,yr}} + W_{P_{rg,yr}} + W_{H_{rg,yr}}$
Next time step (yr + 1) [Trill US$]	$W_{N_{rg,yr+1}}$	$W_{P_{rg,yr+1}}$	$W_{H_{rg,yr+1}}$	–	–
Flow per year [Trill US$/year]	$\delta W_{N_{rg,yr}} = \frac{W_{N_{rg,yr+1}} - W_{N_{rg,yr}}}{10}$	$\delta W_{P_{rg,yr}} = \frac{W_{P_{rg,yr+1}} - W_{P_{rg,yr}}}{10}$	$\delta W_{H_{rg,yr}} = \frac{W_{H_{rg,yr+1}} - W_{H_{rg,yr}}}{10}$	$DC_{rg,yr}$ 2.2.3, Eq. (10)	$\delta W_{N_{rg,yr}} + \delta W_{P_{rg,yr}} + \delta W_{H_{rg,yr}} - DC_{rg,yr}$
Annual rate of change in comprehensive Wealth (%/year)	–	–	–	–	$GS_{rg,yr} = \frac{\delta W_{N_{rg,yr}} + \delta W_{P_{rg,yr}} + \delta W_{H_{rg,yr}} - DC_{rg,yr}}{W_{N_{rg,yr}} + W_{P_{rg,yr}} + W_{N_{rg,yr}}}$

Table 2 Computing framework in this study (*after* adjusting rates of population growth and technological change)

Annual rate of change in comprehensive Wealth (%/year)	Population growth rate (%/year)	Annual rate of change in comprehensive Wealth, after adjusting population change rate (%/year)	Rate of technological change (%/year)	Annual rate of change in comprehensive Wealth, after adjusting rates of population change and technological change (%/year)
$GS_{rg,yr}$	$n_{rg,yr}$ 2.2.4, Eq. (11)	$GS_{n_{rg,yr}} = GS_{rg,yr} - n_{rg,yr}$	$\tau_{rg,yr}$ 2.2.5, Eq. (13)	$GS_{nt_{rg,yr}} = GS_{rg,yr} - n_{rg,yr} + \tau_{rg,yr}$

$$W_{Nm_{rg,yr}} = \sum_{yr' \geq yr}^{\infty} \left(\frac{1}{1 + r_{rg,yr}} \right)^{yr' - yr} \cdot \left(\sum_{mr} nr_{mr,rg,yr} \cdot q_{mr,rg,yr} \right) \tag{3}$$

yr, $yr' = 2010, 2020, \ldots, 2150$, only $yr' \geqq \mathrm{yr}$; $mr =$ mineral resources (fuel mineral resources *fm* (coal, oil, gas, uranium) and non-fuel mineral resources *nfm* (iron ore, bauxite, copper, lead, zinc, limestone).

W_{Nbio} is computed from the bio-products' yields (wood from forests, food from grasslands, and croplands) $B_{bio,rg,yr}$ and rent $nb_{bio,rg,yr}$ (Eq. 4). The computing method of rent is the same as for underground resources. The value of the natural capital stock is computed as shown in Eq. (5).

$$W_{Nbio_{rg,yr}} = \sum_{yr' \geq yr}^{\infty} \left(\frac{1}{1 + r_{rg,yr}} \right)^{yr' - yr} \cdot \left(\sum_{bio} nb_{bio,rg,yr} \cdot B_{bio,rg,yr} \right) \tag{4}$$

$$W_{N_{rg,yr}} = W_{Nm_{rg,yr}} + W_{Nbio_{rg,yr}} \tag{5}$$

$bio =$ wood materials *pw* (logs, wood pulp, timber/boards, papers) and food *fd* (pork, chicken, mutton, beef, rice, wheat, corn).

2.2.2.2 Value of the physical capital stock W_P W_P is the sum of net present value of the infinite stream of the amount of final products (electric machinery products, automobiles, civil engineering, and construction). $MP_{nfm,\mathrm{sec},rg,yr}$ obtained from the mineral resources balance model, multiplied by the rent $np_{nfm,\mathrm{sec},rg,yr}$ (Eq. 6). The computing method of rent is the same as for underground resources.

$$W_{P_{rg,yr}} = \sum_{yr' \geq yr}^{\infty} \left(\frac{1}{1 + r_{rg,yr}} \right)^{yr' - yr} \cdot \left(\sum_{nfm} \sum_{\mathrm{sec}} np_{nfm,\mathrm{sec},rg,yr} \cdot MP_{nfm,\mathrm{sec},rg,yr} \right) \tag{6}$$

$sec =$ Three industrial sectors in the final demands (electric machinery products, automobiles, civil engineering and construction).

2.2.2.3 Value of the human capital stock W_H The aggregate stock of human capital $H_{rg,yr}$ is obtained by multiplying following three terms; the labor population $L_{rg,yr}$[8] by an

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[8] We assumed that people between the ages of 15–64 are all members of the labor population. Based on the medium-scenario population projection by the United Nations (UN World Population 2300), we computed the labor population rate at the time for each area. We then multiplied these figures by the B2 scenario.

individual human capital stock ϕ through average education years S (i.e., $\exp(\phi(\mathrm{S}))$[9]), and human health (i.e., $\exp(\phi \cdot ASR)$[10]) (Ferreira and Hamilton 2010).

$$H_{rg,yr} = \exp(\phi(S)) \cdot \exp(\psi \cdot ASR) \cdot L_{rg,yr} \tag{7}$$

W_H can be obtained by multiplying $H_{rg,yr}$ by its shadow price $pH_{rg,yr}$.

$$W_{H_{rg,yr}} = pH_{rg,yr} \cdot H_{rg,yr}. \tag{8}$$

The shadow price $pH_{rg,yr}$ is computed by dividing the marginal change of social welfare V against the marginal change of aggregate stock of human capital H ($\partial V/\partial H$), by the marginal change of utility against the marginal change of consumption ($\partial U/\partial C$).

$$pH_{rg,yr} = \frac{\partial V/\partial H}{(\partial V/\partial C)/(\partial V/\partial U)} = \frac{V_H}{U_C}. \tag{9}$$

2.2.3 *Flow value of the environmental capital DC*

We adapted a modified version of an impact assessment model for Japanese Life Cycle Impact Assessment (named LIME; Itsubo et al. 2000, 2005, 2012; Itsubo and Inaba 2010) to compute the value of the non-marketed goods. The external costs of the environmental impact can be expressed in the following Eq. (10) using the amount of marginal willingness to pay (MWTP)[11] WF_{sgo,rg,yr_0}, dose–response relationship $DR_{sgo,sbs,rg,yr}$, and inventory $Inv_{sbs,rg,yr}$. We consider environmental external costs obtained from Eq. (10) would occur as a flow in negative value. We therefore subtract this value from changes of wealth, as is expressed in Eq. (2).

$$DC_{rg,yr} = \sum_{sgo} WF_{sgo,rg,yr} \cdot \sum_{sbs} DR_{sgo,sbs,rg,yr} \cdot Inv_{sbs,rg,yr} \tag{10}$$

sgo = subjects of protection (human health (*hh*), social assets (*soc*), net primary productivity (*npp*), biodiversity (*bd*)), sbs = greenhouse gas (*ghg*), ozone layer depletion substances (*ods*), extraction and disposal of non-fuel mineral resources (*met*), land use and change (*lnd*).

2.2.4 *Annual population growth rate n*

For the population, as the exogenous population scenario $N_{rg,yr}$ for a given time in a given area, we used the B2 story line of the Special Report on Emissions Scenarios (Nakićenović and Swart 2000) (IPCC-SRES-B2) and computed the population growth rate using Eq. (11).

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[9] Form of function ϕ is a diminishing return ($\phi' = \mathrm{d}\phi/\mathrm{dS} > 0$, $\phi'' = \mathrm{d}^2\phi/\mathrm{dS}^2 < 0$), when ϕ equals zero when S is zero. ϕ' is marginal income increase by additional education attainment, corresponds to coefficient (rate of return). ϕ was computed from data in Cuaresma and Lutz (2007), Hall and Jones (1999), Psacharopoulos (1994), Psacharopoulos and Patrinos 2004, Barro and Lee (2010), and World Bank (2010).

[10] Adult Survival Rate (ASR) is 1-AMR (Adult Mortality Rate). AMR is weighted average of male and female adult mortality rates taken from the WDI 2010 (“Mortality rate, adult, male”, “Mortality rate, adult, female”, and “Population, female (% of total)”). Then AMR is expressed as a function of per capita GDP in respective 10 regions. ψ is set .653 from Weil (2007). see detail in Ferreira and Hamilton (2010).

[11] We undertook a social survey of 1,000 people all over Japan in 2006. Based on the survey results, we carried out conjoint analysis to obtain willingness to pay (WTP) (Itsubo et al. 2012). We then applied benefit transfer to areas other than Japan and to a future time point by using elasticity for per capita GDP, based on the review by Pearce (Pearce 2003).

$$n_{rg,yr} = \left(N_{rg+1,yr}/N_{rg,yr}\right)^{1/10} - 1. \tag{11}$$

2.2.5 Annual technological change rate τ

"Technological change" in this paper is set as a calibration shown in Eq. (12). We set $A_{rg,yr}$ as a multiplier to of the production function $F_{rg,yr}(K, H, E, M, LU)$, which is equal to the sum of the reference GDP based on the IPCC-SRES-B2 scenario ($refGDP_{rg,yr}$) and the costs of the intermediate goods (energy, mineral resources, land use, external costs).

$$A_{rg,yr} = \frac{refGDP_{rg,yr} + EC_{rg,yr} + MC_{rg,yr} + LUC_{rg,yr}}{F_{rg,yr}(K, H, E, M, LU)}. \tag{12}$$

We computed $\tau_{rg,yr}$ from the above $A_{rg,yr}$, as shown in Eq. (13).

$$\tau_{rg,yr} = \left(A_{rg,yr+1}/A_{rg,yr}\right)^{1/10} - 1 \tag{13}$$

3 Computing results

3.1 Base case

3.1.1 Product amount, rent, shadow price

Figure 1 shows the transition of the production of the physical and natural capitals and aggregates stock of human capital (the multiplication of an individual human capital stock by the labor population) whose orders are in 10^9. The three terms (civil engineering and

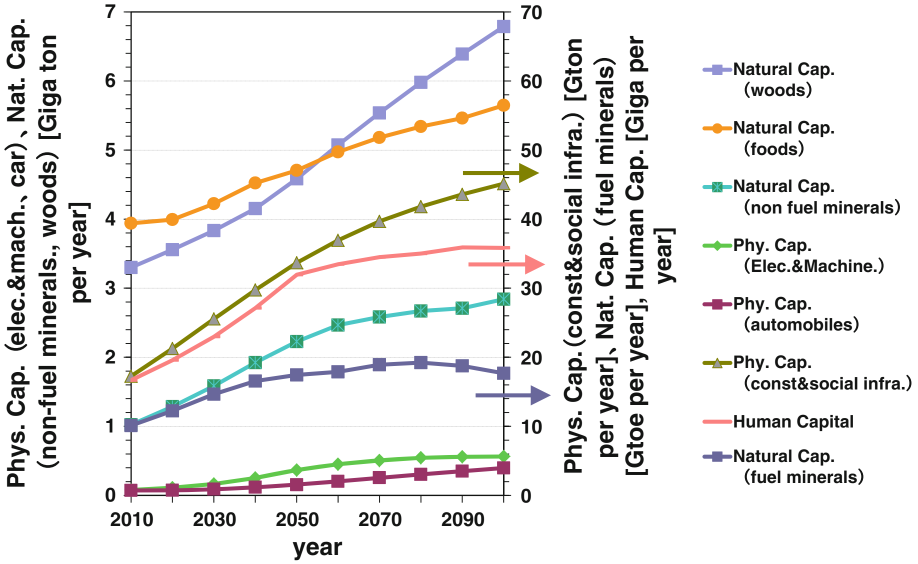

Fig. 1 Trajectories of production of physical capital and natural capital, and an aggregate stock of human capital (multiplying labor population by an individual human capital stock) in global total

construction of the physical capital, fuel minerals of the natural capital, and aggregate stock of human capital (right axis)) are one order larger than the remaining four (left axis).

This result largely depends on the exogenously given scenario. For example, the final energy demands (transportation, electricity, and thermal energy) were based on the IPCC-SRES-B2 scenario. The final energy demands would become approximately 1.7 times larger in 2100 compared with 2010, while production of natural capital (fuel minerals) would be twice as large in the same period (resources other than fuel mineral resources will be compensated by the growth of renewable resources). Similarly, the demand scenario of the final products, which was estimated using the population and GDP based on the IPCC-SRES-B2 scenario, became three times larger (of which cement was 2.6 times larger) during the same period. Because of this final product growth, the natural capital (metal minerals) and physical capital (civil engineering and construction) show a trend similar to that of cement (limestone).

Figure 2 shows the trajectories of the rents of physical capital and natural capital, and the shadow price of the human capital, respectively. The rents do not show a large fluctuation, and we cannot establish clear reasons for the trajectories of the natural capitals (fuel mineral and foods), physical capital (civil engineering and construction), and human capitals. However, we think that, because the natural capital (fuel minerals) and physical capital (civil engineering and construction) were illustrated through weighted averages according to their production, they showed a declining trend since they were affected by resources produced in huge amounts with declining rents (oil, coal, and limestone). We think our setting of the gradual decrease of individual human capital stock according to per capita GDP growth causes a declining trend for human capital.

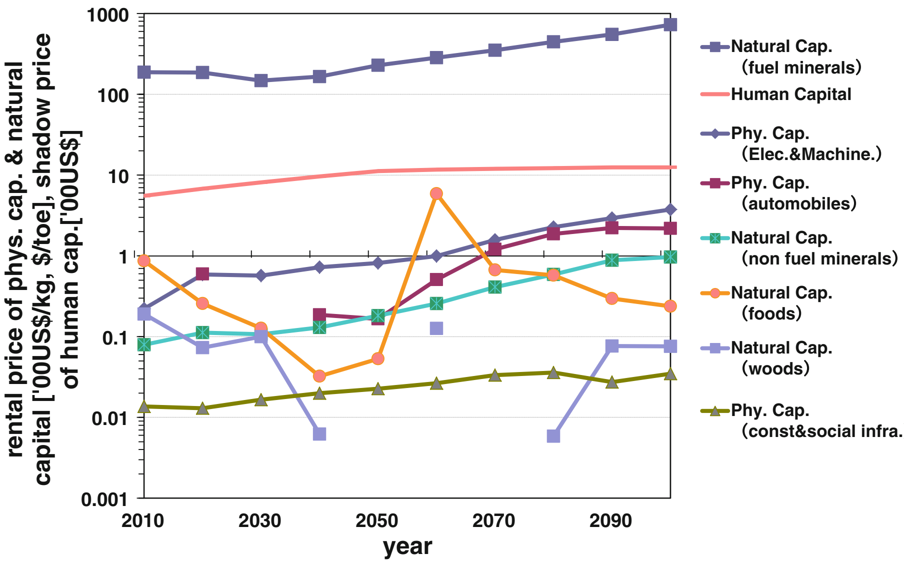

Fig. 2 Trajectories of rent for physical capital, natural capital, and shadow price of human capital, in global total

3.1.2 Value of the capital stocks

The values of each capital stock using Eqs. (5), (6), and (8) are shown in Fig. 3. Changes in Wealth are obtained from the multiplication of changes in rent and those in production. The result indicates that changes in Wealth are affected mainly by changes in production, rather than those in rent. For the entire capital, total natural capital, and physical capital, all became 2.7–2.9 times larger in the year 2100 compared with the year 2010. The largest increase among terms in the graph is in natural capital (fuel minerals). The rates of each capital were approximately 10 % for physical, 50 % for natural (fuel minerals), 10 % for natural (metal minerals), and some 30 % for natural (foods), respectively.

3.1.3 Changes of wealth (genuine saving; GS)

3.1.3.1 Results for the world for the year 2040 Tables 3 and 4 present an example of the results of calculating changes of wealth for the world for the year 2040, based on the computing framework of this study. Each value of the three capitals and the total values of the capitals in the year 2040 and 2050 correspond to Fig. 3. The flow value of each capital in Table 3 was computed by dividing changes of each capital by 10 years. The total flow value (19) was obtained by subtracting the environmental impact (12) from the total figures (30 + 1 − 12). This value was divided by the aggregated current value of these capitals (689) to reach 2.83 % for the "annual changes of the comprehensive wealth (corresponds to GS)."

The "annual changes of the comprehensive wealth (GS)" in Table 3 corresponds to the left end of Table 4. "GSn (GS adjusted by the population growth rate; 2.35)" can be obtained by subtracting annual population growth rate (2.83) from GS (0.48). We furthermore can obtain 5.24 for the "GSnt (GS adjusted by annual population growth rate and annual technological changes," by adding technological changes (2.88) to GSn.

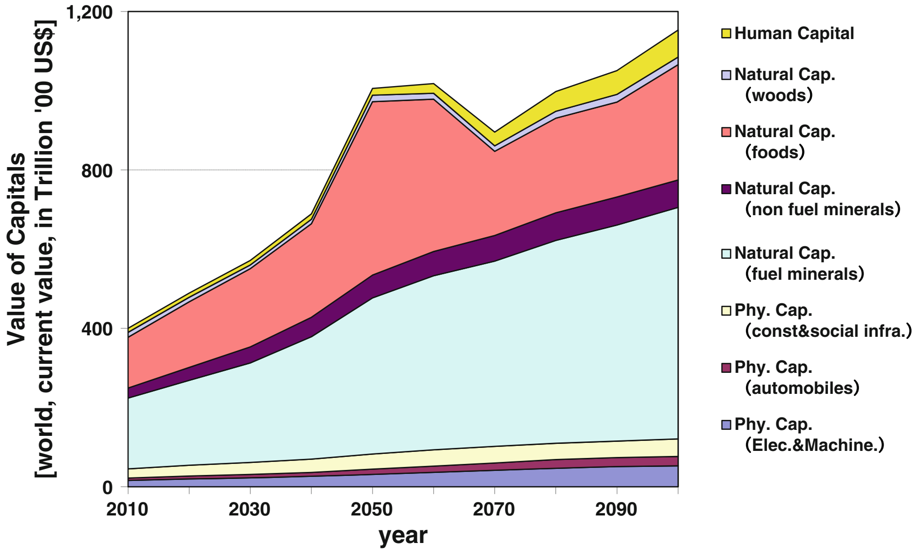

Fig. 3 Trajectories value of respective capitals in global total

Table 3 Results for global and 2040 as current time step, based on the computing framework in this study (*before* adjusting rates of population growth and technological change)

	Natural capital	Physical capital	Human capital	Environmental impact	Summation
Year in 2040 [Trill'00 US$]	606	70	14	–	689
Year in 2050 [Trill'00 US$]	906	83	17	–	1,006
Flow per year [Trill'00 US$/year]	30	1	0	12	19
Annual rate of change in comprehensive Wealth (GS) (%/year)	–	–	–	–	2.83 %

Table 4 Results for global and 2040 as current time step, based on the computing framework in this study (*after* adjusting rates of population growth and technological change)

Annual rate of change in comprehensive Wealth (GS) (%/year)	Population growth rate (%)	Annual rate of change in comprehensive Wealth, after adjusting population change rate (GSn) (%/year)	Rate of technological change (%/year)	Annual rate of change in comprehensive Wealth, after adjusting rates of population change and technological change (GSnt) (%/year)
2.83	0.48	2.35	2.88	5.24

3.1.3.2 Transition of the changes of wealth Figure 4 presents transitions of GS, GSn, and GSnt according to a calculation framework in Tables 3 and 4, the growth rate of the Gross World Product (GWP). The GS, GSn, and GSnt show an increasing trend until 2040 and then turn into a decreasing trend afterward. GSnt is relatively closer trend to that of GWP growth rate than those of GS and GSn, which are almost always lower than the GWP growth rate. GWP will continuously grow within the time horizon; however, GS shows lower figures than that of GWP. GSnt satisfies the necessary condition for "sustainable development (SD)" during the twenty-first century at several time steps; however, the requirement is not met by GSn or GS in most of the twenty-first century.

3.2 Results in a different scenario

3.2.1 Scenario description

The above result is based on the scenario of population and Gross World Product (GWP) in IPCC-SRES-B2 (hereafter referred to as "B2-optimal" case). The B2-optimal are so called "economically efficient" paths in the sense that the environmental externalities are internalized into macro-economy, like the "optimal" case in the DICE and RICE models by Nordhaus (e.g., Nordhaus 1994; Nordhaus and Boyer 2000). In this section, following additional three cases are presented; (1) adding CO_2 constraint (550 ppm) on the B2-optimal case ("B2-CO_2" case), (2) dramatically decreasing population after the latter half of the twenty-first century (IPCC-SRES-B1) ("B1-optimal" case), and (3) adding the same CO_2 constraint on the B1-optimal case ("B1-CO_2" case). Illustrations of CO_2 emissions, population, and GWP in these four scenarios are presented in Fig. 5.

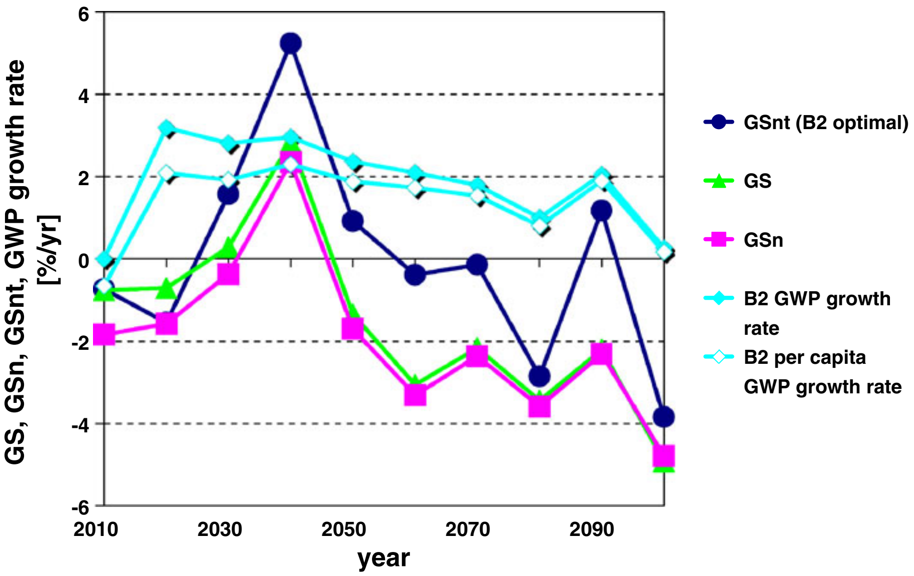

Fig. 4 Trajectories of changes of wealth (i.e., genuine saving; GS) in global total. GS corresponds to GS without adjusted rates of population growth and technological change, GSn means GS with adjusted population growth rate and without technological change, GSnt with both rates

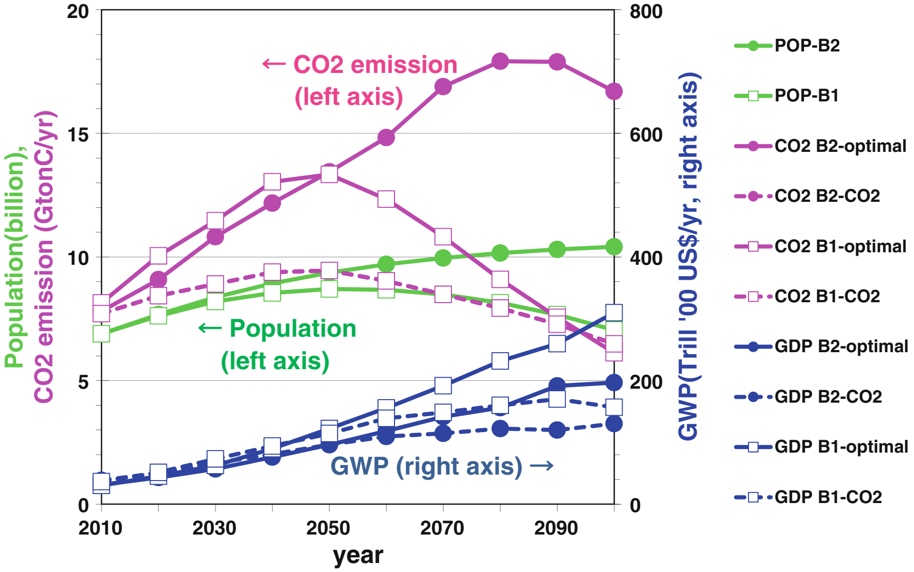

Fig. 5 Trajectories of given population scenarios, obtained Gross World Product (GWP), and results of CO_2 emissions for the four cases in this study (in global total)

In the B2-optimal scenario, the population (in green) will grow from approximately 6 billion at present to 10 billion in 2100; GWP (in blue) will be five times larger (from approximately 40 trillion \$/year to 200 trillion \$/year), and CO_2 emissions (in pink) will increase by 2.5 times (8 GtonC/year to 18 GtonC/year).

In B2-CO_2 scenario compared to that of B2-optimal, GWP growth would gradually slow down after 2050, reaching 130 trillion \$/year, with the same population growth rate of the B2-optimal scenario. The CO_2 emission would dramatically decrease after 2050, reaching in 2100 slightly lower than current emission level, approximately one-third of B2-optimal case in 2100. The CO_2 constraint is met by reducing economic growth by 30 % in this case.

A trajectory of GWP in B1-optimal case is larger than that of B2-optimal by some 50 %; however, the population scenario of B1 gradually decreases after 2050, reaching 30 % less than that of B2-optimal in 2100. CO_2 emission of B1-optimal is the same as or slightly larger than B2-optimal until 2050; however, it decreases dramatically afterward to reach same level as of B2-CO_2 in 2100. The population of B1 is 30 % smaller than that of B2, while GWP is some 50 % larger than that of B2-optimal; hence, the per capita GDP growth rate for the B1-optimal scenario is originally set larger than that of B2-optimal. The B1-CO_2 case is obtained by binding the CO_2 emissions profiles same as that of B2-CO_2, resulting GWP by some 50 % lower than that of B1-optimal.

3.2.2 Comparison of the results of wealth and per capita wealth

Figure 6 shows the trajectories of wealth and per capita wealth. First, we compare cases between the B2-optimal with the B2-CO_2. Wealth of B2-optimal shown in Fig. 3 corresponds with the top solid blue line with circles, and per capita wealth of B2-optimal corresponds with the solid pink line with circles, fourth from the bottom. Wealth of B2-CO_2 corresponds to second from the top with the dotted blue line with circles, and the per

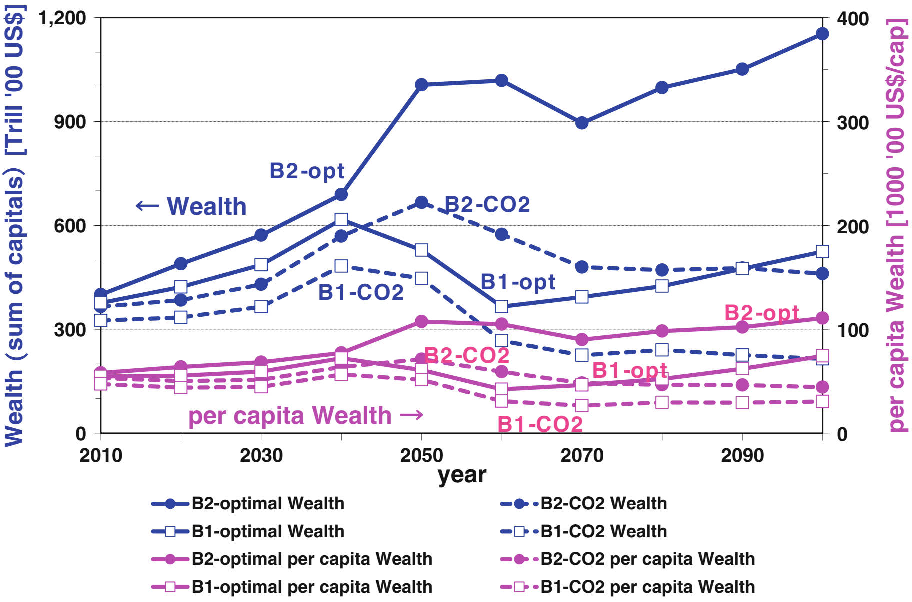

Fig. 6 Trajectories of wealth and per capita wealth for the three cases in this study (in global total)

capita wealth of B2-CO_2 corresponds to the dotted pink line with circles, third from the bottom.

The wealth (and per capita wealth) of B2-CO_2 decreases by half at the most compared to B2-optimal in order to satisfy CO_2 constraint by reducing GWP and environmental external costs by 30–40 %, via reducing by 30 % production of natural capital (fuel and non-fuel mineral resources) that flows to the production function. The production of physical capital (civil engineering and construction, automobiles, electricity and machinery products) has resulted in decrease by 30 %, mainly due to decrease in demand according to that in GWP as well as that in production of natural resources. Rent changes little compared to production because both shadow prices and production costs have increased. Wealth then largely decreased according to the production reduction.

The GWP of the B1-optimal scenario becomes some 50 % larger than that of B2-optimal, since the figure of technological change in B1-optimal is higher than that in B2-optimal, though the value of the production function, intermediate costs, and external costs had declined as a result of decreasing physical and natural capitals in B1-optimal. The wealth of the B1-optimal case shows reduced gradually from that of B2-optimal from 2050 and will have declined by 50 % by 2100. Both wealth and per capita wealth of B1-CO_2 reduced by about half after 2050 compared to B1-optimal.

3.2.3 *Comparison of GSnt (Genuine Saving adjusted by rates of population growth and technological change)*

Figure 7 presents GSnt for the four cases. B2-optimal case corresponds to that of GSnt in Fig. 4. GSnt results in similar trends in these cases. GSnt starts from negative, increasing till 2040, then gradual decrease thereafter. Optimal cases show relatively higher value, showing positive value of GSnt in some time steps meaning to meet necessary conditions of sustainable development, than those of CO_2 cases.

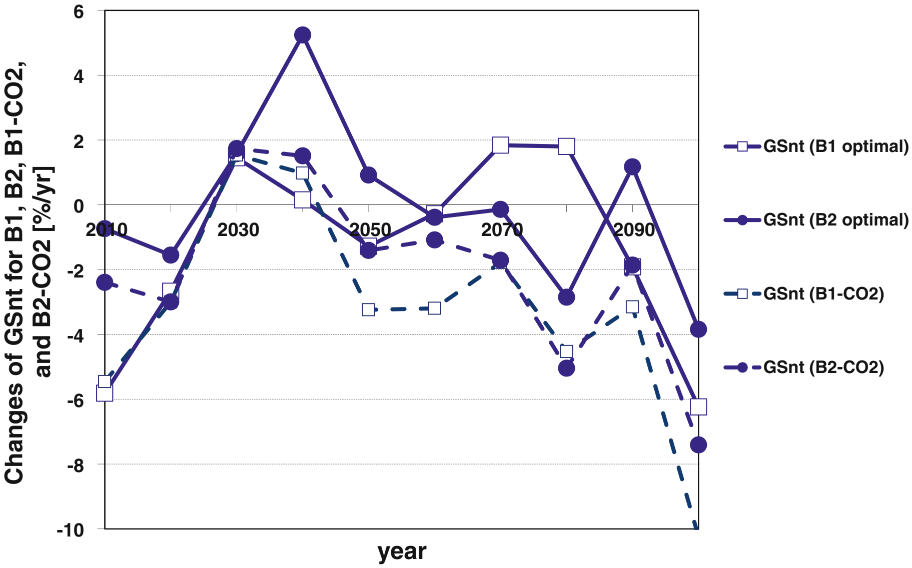

Fig. 7 Trajectories of GSnt for the four cases in this study (in global total)

The cases of B1-optimal and B2-optimal are so called “economically efficient” paths in the sense that the environmental externalities are internalized into macro-economy, like the “optimal” case in the DICE and RICE models by Nordhaus (e.g., Nordhaus and Boyer 2000). The models indicate carbon shadow prices with CO_2 constraints exceed that of the “optimal” case. The result of GS in B2-CO_2 case might suggest that CO_2 constraint over “optimal” case could lead to declining GS.

4 Conclusion

This study took climate change mitigation directory into consideration for macroeconomic indicators of sustainable development, to advance preceding studies both in economics and climate change mitigation. We expanded an existing integrated assessment model to measure the future dynamics of GS and wealth under IPCC SRES with CO_2 emissions constraints. GS is obtained from changes of wealth, which is computed from the value of capital stocks as a product of output and rent, following Kunte et al. (1998). It turned out that GS values can be largely affected by production quantity, especially output decreased by CO_2 emissions constraints in our model. Results indicated that GSnt starts from negative, increasing till 2040, then gradual decrease thereafter. Optimal cases show relatively higher value, showing positive value of GSnt in some time steps meaning to meet necessary conditions of sustainable development, than those of CO_2 cases. This inclination might lead us to argue somewhat paradoxically that controlling CO_2 emissions path well below “optimal” path does not enhance sustainability; however, it is too early to confirm such a conclusion before further investigating scenario analysis as well as refining our model. The current paper has shown that adopting an integrated assessment model to measure GS and wealth helps us to better understand not only economics of sustainability, but also the consequences of climatic change mitigation policies.

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Appendix

A brief outline of our model

Objective function

We assume a social planer who maximizes (intertemporal) social welfare, $V(t)$, expressed by the present discounted value of utility streams:

$$\max V(t) = \int_{s=t}^{\infty} N(s) \cdot \log\left(\frac{C(s)}{N(s)}\right) \mathrm{e}^{-\rho(s-t)} \mathrm{d}s \tag{14}$$

where $N(s)$ is population (exogenously given), $C(s)$ is consumption (endogenous), utility is given by the product of the logarithm of per capita consumption and population, and ρ is the pure rate of time preference or utility discount rate, assumed to be 2 %/year here (see Appendix, Table 5). Here, a caution is warranted that our model is described not in continuous time, but in terms of 10-year time steps (denoted as “yr” hereafter) from 2010 to 2150. The period after 2150 is added by using the sum of an infinite geometric series

Table 5 Nomenclature of mainframe of the model

Exogenous data	L	Labor force (population aged 15–64)
	N	Population
	n	Population growth rate
Endogenous variables	A	TFP (used as a calibration factor, similar to the Solow residual)
	C	Aggregate consumption
	c	Aggregate consumption per capita
	DC	Environmental damage cost
	EL	Electricity
	F	Production function
	FC	Cost of energy supply chain
	g	Growth rate of per capita consumption
	H	Aggregate stock of human capital
	I	Investment in the physical capital
	Ie	Education expenditure
	IM	Import
	K	Aggregate stock of physical capital
	LU	Land use
	LUC	Cost of LU&LUC with food supply chain
	M	Non-fuel mineral resources
	nb	Resource rental for bio-products
	NE	Non-electric energy resources
	NFC	Cost of non-fuel minerals supply chain
	nr	Resource rental for natural resources
	np	Resource rental for physical products
	pH	Shadow price of aggregate stock of human capital
	q	Amount of resource extraction
	r	Consumption discount rate
	S	Average education years
	U	Utility
	XP	Export
	Y	Gross domestic product
Constant parameters	a_1, a_2, a_3	Calibration factors
	Neg	Negishi weight
	α,β,γ	Value share of capital, electricity, energy, in respective input factors
	δ	Depreciation rate of physical capital
	ε, λ	Elasticity of substitution
	φ	Individual human capital stock
	ρ	Pure rate of time preference, utility discount rate
	ψ	Term used in capital stock for human health
	σ	Income elasticity for benefit transfer

(unshown in Eq. 15). Geographically, the model divides the world into ten regions (denoted as “rg” hereafter), which are North America, Western Europe, Japan, Oceania, China, East-South Asia (including India), Middle East and North Africa, Sub-Sahara Africa, Latin America, and the former Soviet Union and Eastern Europe. Hence, Eq. (14) is expressed as follows, where c is per capita consumption:

$$\max V(2010) = \sum_{rg} Neg_{rg} \cdot \left(\sum_{yr=2010}^{2150} \left(\frac{1}{1+\rho} \right)^{yr-2010} \cdot N_{rg,yr} \cdot \log c_{rg,yr} \right) \tag{15}$$

For population, the scenario from the Special Report on Emissions Scenarios (SRES) by the IPCC (Intergovernmental Panel on Climate Change) is used as exogenous scenario $N_{rg,yr}$ by time step and world region. Neg_{rg} is known as the “Negishi weight,” whose interpretation is that “optimization” determines the efficient competitive-market equilibrium of the different regions.

A macro-economy submodel

Consumption is derived endogenously within a model, similar to the RICE (Nordhaus and Boyer 2000), in which macroeconomic relations are determined among output, investment, capital stock depreciation, intermediate inputs (supply cost of fuel mineral resources, non-fuel mineral resources, and land use), and external damage costs. Specifically, we have:

$$C_{rg,yr} = Y_{rg,yr} - I_{rg,yr} + IM_{rg,yr} - XP_{rg,yr} \tag{16}$$

where output, *Y*, is given by the nested production function, subtracted by costs involved in intermediate inputs such as *FC, NFC, LUC, DC*:

$$Y_{rg,yr} = A_{rg,yr} \cdot F_{rg,yr}(K, H, EL, NE, M, LU) - FC_{rg,yr} - NFC_{rg,yr} - LUC_{rg,yr} - DC_{rg,yr} \tag{17}$$

$$F_{rg,yr}(K,H,EL,NE,M,LU) = \left[\left[\left\{ a_1 \left(K_{rg,yr}^{\alpha} H_{rg,yr}^{1-\alpha} \right)^{-\varepsilon} + a_2 \left(\left(EL_{rg,yr}^{\beta} \cdot NE_{rg,yr}^{1-\beta} \right)^{\gamma} \cdot M_{rg,yr}^{1-\gamma} \right)^{-\varepsilon} \right\}^{-\frac{1}{\varepsilon}} \right]^{-\lambda} + a_3 \cdot LU_{rg,yr}^{-\lambda} \right]^{-\frac{1}{\lambda}} \tag{18}$$

where *K* is physical capital stock, *H* is human capital, *EL* is electricity, *NE* is non-electric energy resources, *M* is non-fuel mineral resources, *LU* is land resources, and a_1, a_2, a_3, α, β, γ, ε, λ are the parameters. The dynamics of the capital stock is described by:

$$K_{rg,yr+1} = (1-\delta)^{10} \cdot K_{rg,yr} + I_{rg,yr} \tag{19}$$

where δ is the annual depreciation rate.

$A_{rg,yr}$ is the calibration term between $F_{rg,yr}$ (*K,H,EL,NE,M,LU*) and the sum of intermediate input costs ($FC_{rg,yr} + NFC_{rg,yr} + LUC_{rg,yr}$) plus value added ($refGDP_{rg,yr}$), which is the benchmark GDP of SRES-B2 scenario adopted in Nakićenović and Swart (2000):

$$A_{rg,yr} = \frac{refGDP_{rg,yr} + FC_{rg,yr} + NFC_{rg,yr} + LUC_{rg,yr}}{F_{rg,yr}(K, H, EL, NE, M, LU)} \tag{20}$$

The aggregate stock of human capital $H_{rg,yr}$ is obtained by multiplying labor population $L_{rg,yr}$ by an individual human capital stock ϕ through average education years $S_{rg,yr}$ (i.e., exp(ϕ(S))), and human health (i.e., exp(Ψ *ASR*)).

$$H_{rg,yr} = \exp(\varphi(S)) \cdot \exp(\psi \cdot ASR) \cdot L_{rg,yr} \tag{21}$$

$FC_{rg,yr}$, $NFC_{rg,yr}$, $LUC_{rg,yr}$, $DC_{rg,yr}$ are fuel mineral supply cost, non-fuel mineral supply cost, land-use cost for food supply, and damage cost, respectively, which are explained in the following sections.

Fuel and non-fuel minerals (FC, NFC)

The submodel 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 electrical or chemical conversion process for energy, transportation among the ten global regions, to the final demand of both energy ($EL_{rg,yr}$ and $NE_{rg,yr}$) and materials ($MD_{\mathrm{sec},nfm,rg,yr}$) by three representative manufacturing sectors (electricity and machinery, construction and building, motor cycles). The nfm exist as in-use stocks of goods produced during the assumed products lifetime, after which they become out-of-use stocks and then are finally disposed of or recycled.

Land use and land-use change (LUC)

The land-use submodel calculates the endogenous five categories of land use (forestry, grassland, cropland, urban, others) and 20 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 the use of exogenous costs of land rent, land conversion, and food production.

The food demands are expressed as both calorie based and protein based, which are satisfied by crop productions in croplands and by meat productions in grasslands. Each production is converted by use of yield to area of cropland and grassland (pasture land). The area of urban land is calculated from population and population density. Forest area is calculated via (1) deforestation and reforestation due to carbon release and absorption, (2) conversion to cropland and grassland for food production requirements. The land category of "other" includes all others such as desert terrain 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 grassland and cropland satisfy aggregated food demand.

External damage costs (DC)

Damage cost (DC) can be calculated by:

$$DC_{rg,yr} = \sum_{sgo} WF_{sgo,rg,yr} \cdot \sum_{sbs} DR_{sgo,sbs,rg,yr} \cdot Inv_{sbs,rg,yr} \tag{22}$$

where

$$WF_{sgo,rg,yr} = WF_{sgo,JPN,yr_0} \cdot \left(\frac{Y_{rg,yr} / N_{rg,yr}}{Y_{JPN,yr_0} / N_{JPN,yr_0}} \right)^{\sigma} \tag{23}$$

sgo = human health, social capital, net primary production (NPP), and biodiversity, sbs = greenhouse gases, ozone depletion substances (ODS), extraction and disposal of nfm, LU&LUC.

The weighting factor, *WF* (or MWTP), and the dose–response relation, *DR*, are exogenously given by LIME. They are related to four endpoints (or safe guard objects) by way of the DR relationship described in (Itsubo and Inaba 2000; Itsubo et al. 2005) then aggregated into monetary terms by *WF* obtained through conjoint analysis (Itsubo et al. 2005, 2012). *INV* is inventories treated in the model, such as CO_2, SO_x, and NO_x from fuel combustion, CO_2 release via deforestation, five kinds of non-CO_2 greenhouse gas GHG (NCGHG), 14 kinds of ozone depletion substances (ODS), and extraction and disposal of nfm, LU&LUC. NCGHG and ODS are exogenous; all the others are endogenous. DR and WF in LIME are adjusted to be compatible with all regions and time steps in our model. The WF is transferred by using benefit transfer expressed in Eq. (A10) (income elasticity σ of 0.5 from Pearce 2003).

The Dose–Response relations in Japan are indicated in LIME, which is adjusted to all regions and time steps to suit our model. 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 (Kosugi et al. 2009). 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 by values of dose–response in present-day Japan. The ratio of population density ratio for human health, the ratio of population density 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.

Impact categories treated in our model (see Appendix Table 6)

Global warming

In order to develop damage functions for the safeguard subjects of human health (WHO 2010), social assets (Uchida et al. 2002) and biodiversity (Thomas 2004), (1) damage due to the impact pathway with and without emissions perturbations for CO_2, NOx, SOx, as was carried out in papers by R.S.J. Tol (e.g., Tol 2005), by using the MAGICC/SCENGEN 5.3 model (Wigley 2010); (2) time series impacts were estimated by interpolation and extrapolation based on the benchmark impacts considering regional population change and economic development (United Nations 2003, Nakićenović et al. 1998, WHO 2004); (3) the damages were aggregated as functions of global mean temperature rise.

Damages for human health The human health impacts till the end of this century are extrapolated from WHO 2004, for malaria, diarrhea, malnutrition, coastal floods, inland floods and landslides. The damage is calculated between damages between with and without the perturbations for the following equation: (global mean temperature rise) * (baseline scenario for outbreaks of illness) * (relative risks $-$ 1) * (baseline scenario for population) * (DALY per case).

Damages for social capital stock Future crop productions without CO_2 fertilization effects were extrapolated results from 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

Table 6 Category endpoints considered in LIME in relation to impact categories and safeguard subjects

Impact category	Safeguard subject			
	Human health	Social capital stock	Biodiversity	Primary productivity
Global warming	Malaria, diarrhea, malnutrition, coastal floods, inland floods and landslides (WHO 2004)	Crop production, Land submergence, Energy consumption (Uchida et al. 2002)	Extinction risks (Thomas 2004)	
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. 2002)		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)

consumption was analyzed using empirical energy consumption data for Japan (EDMC/IEEJ 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.

Damages for biodiversity Relationships between relative change for land use and global mean temperature are derived from Thomas 2004 using species-area relationships. The impacts are converted into relative risk changes modeled in the original LIME model (Itsubo 2010), as a function of global mean temperature rise.

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).

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.

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) were utilized for the actual NPP.

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