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Development of weighting factors for G20 countries. Part 2: estimation of willingness to pay and annual global damage cost

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Abstract

Purpose This paper is the second part of a series of articles presenting the results of research on monetary weighting factors (MWFs) for the G20 countries, which together account for approximately 90% of the global GDP. We developed their MWFs with regard to Life Cycle Impact Assessment (LCIA) and evaluated them via a large-scale questionnaire survey. We estimated the economic value of one unit of damage caused by human activities.

Methods To ensure that the MWFs covered all areas of protection as defined by the LCIA method based on Endpoint Modeling (human health, social assets, biodiversity, and primary production), we conducted a choice experiment in all G20 countries. We conducted face-to-face interviews to minimize survey bias and ensure that the questions were understood by the emerging G20 countries' respondents. Internet surveys were adopted to collect samples from the developed G20 countries' respondents, where Internet diffusion rates are generally high. We obtained response data from 200 to 250 and 500 to 600 households of all the emerging and all the developed G20 countries, respectively. We gathered 6400 responses in all. We estimated preference intensities using the random parameter logit model. We calculated MWFs based on each respondent's willingness to pay.

Results and discussion We devised MWFs providing the costs of damage to four safeguard subjects. All the estimated values are statistically significant at the 1% level, with the exception of monetary attributes from Mexico. The MWFs for the G20 are 23,000 USD for human health (per year), 2.5 USD for social assets (per USD of resources), 11 billion USD for biodiversity (per species), and 5.6 billion USD for primary production (per 100 million tons). The differences between the developed and emerging G20 countries are considerable, with the values generally being smaller for the latter in purchasing power parity (USD) terms. The estimated global total economic annual impact was approximately 5.1 trillion USD (6.7% of the world's total GDP).

Conclusions We obtained reasonable and conservative global-scale MWFs compared with previous studies. Moreover, the cross-country heterogeneity in this study potentially helps extrapolate future/global value developments from current/local estimates. The variations in human health and social asset MWFs are small enough within developed countries to allow international transfers among them, while significant variations in biodiversity and primary production MWFs are a caveat to up-front international transfers even within developed countries.

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1 Introduction

Weighting is essential to convert the various types of environmental impacts into a common indicator using numerical factors based on value choices. Despite the integration of social, political, and ethical values being a controversial topic, weighting is frequently used in Life Cycle Assessment (LCA) studies because of its manageability and comprehensibility. Weighting is defined as one of the steps of LCA (ISO 14040 2006; ISO 14044 2006), and to date, a variety of approaches have been developed in this regard.

The various methods of assessment with the use of weighting factors can be classified as proxy method, midpoint method, and endpoint method (Itsubo et al. 2015). The endpoint method is further classified into two types. In the first type, normalized midpoint scores are weighted among endpoints, and in the second, weighting is performed by multiplying the value per unit of damage to the endpoint and the result of endpoint characterization. Economic assessments are classified as belonging to the latter type. The results of an economic assessment are expressed in monetary values, thus making them easy to understand and communicate as well as allowing their application to cost-effectiveness analyses, among others. On the other hand, methods for converting environmental impacts resulting in health damage and ecosystem decline into economic values are still in the development phase. These results may be strongly biased or incomplete, and their use is often inappropriate depending on how the information is conveyed. It is often difficult to assess such impacts in the first place, given the paucity of information and extensive assumptions.

According to Huppes and Oers (2011), economic assessments are classified into the two approaches: integrated modeling (i.e., External Costs of Energy (ExternE); New Energy Externalities Development for Sustainability (NEEDS, 2006); Weitzman 2007; Tol 2008) or weighting in LCA (i.e., Environmental Priority Strategies (EPS)(Steen, 1999); Life Cycle Impact Assessment Method based on Endpoint Modeling (LIME); Weidema 2009). With respect to the former, while Weitzman (2007) and Tol (2008) evaluated specific domains such as climate change and resource depletion, NEEDS and ExternE offer the advantage of broader domain coverage. Whereas the damage costs of the endpoints are always expressed in monetary values in integrated modeling, such simplification and accumulation is inappropriate, because different types of costs (e.g., market values (repair or replacement) or non-market values (contingent valuation, travel cost, and hedonic pricing) and use or non-use values) are adopted depending on the domains.[1] For example, NEEDS adopts restoration costs (ecosystem health), damage costs or abatement costs (climate change), restoration costs

(building materials), and yield (crops) as willingness-to-pay (WTP).[2] In addition, the absence of direct weighting across these terms ensures that integrated modeling does not meet the requirements of ISO 14040.

EPS, which is categorized as a weighting approach in LCA, provides monetary evaluation (i.e., WTP) of multi-endpoints related to the four safeguard areas of human health, ecosystem production, biodiversity, and abiotic stock resources. This methodology covers broader domains such as climate change, air pollution, and resource consumption. However, the result of the EPS is not based on the direct weighting procedure among endpoints, but rather, on the WTP that has been estimated by several previous studies conducted in different countries at various points in time. Since it is presumed that WTP varies depending on economic, cultural, and social conditions, such oversimplified accumulation and treatment of these values provides inconsistent results.

Conversely, LIME, another weighting approach in LCA, directly weights the four areas of protection—human health, social assets, biodiversity, and primary production—using choice experiments. In this study, the monetary term (i.e., environmental tax) was included in the questionnaire so that the respondents could directly compare the importance of the four safeguard subjects and the changes in income due to the levying of the environmental tax. Then, WTP for a unit of each safeguard subject can be calculated using a uniform model (Itsubo et al. 2012, 2015). In addition, LIME has broader domain coverage (15 impact categories as midpoint levels) and also considers aspects such as climate change, air pollution, resource consumption, and acidification.

While LIME2 (Itsubo et al. 2012) developed national weighting factors for Japan (which cannot be used universally as they are specific to Japan), LIME3 (Itsubo et al. 2015 and this study) conducts a large-scale simultaneous survey in the G20 countries, using a uniform questionnaire to compare the weighting factors calculated for different countries and to calculate global-scale weighting factors. Part 1 of this paper (Itsubo et al. 2015) solely presented the dimensionless weighting factors, which are normalized to ensure that the total sum of the values for the four safeguard subjects would be 1 focusing on relative awareness among these subjects. Thus, this study is the first to collate evidence on monetary weighting factors (MWFs) on a global scale. The study thus sheds new light on how the MWFs of developing G20 countries differ from those of the developed G20 countries and provides useful information for economic evaluation in future LCA and cost–benefit analysis (CBA) studies considering the global supply

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[1] LIME adopts non-market values including non-use values via choice experiments. For more details on value categories, see Turner et al. (1994).

[2] NEEDS developed the methodology for ExternE, a series of projects that evaluates environmental impacts due to energy generation and transportation and its external costs, focusing on air pollution and climate change. Note that ExternE does not cover global environmental impacts such as water resource consumption.

Table 1 Attributes and levels used in the choice experiment

	L_1	L_2	L_3	L_4
Human health (loss of health per person)	Status quo (lose 4 days a year)	1/2 (lose 2 days a year)	1/4 (lose 1 day a year)	No loss of life
Social assets (loss of natural resources per person)	Status quo (lose 60 USD a year)	1/2 (lose 30 USD a year)	1/4 (lose 15 USD a year)	No loss of resources
Biodiversity (loss of species)	Status quo (100 species extinct a year)	1/2 (50 species extinct a year)	1/4 (25 species extinct a year)	No species extinct
Primary production (loss of forests)	Status quo (20 billion tons a year)	1/2 (10 billion tons a year)	1/4 (5 billion tons a year)	No loss of forests
Additional tax (yearly per household)	No additional expenditure	Additional 100 USD yearly	Additional 200 USD yearly	Additional 300 USD yearly

chain. Moreover, recent LCA studies use an expanded geographic scope (Hoekstra and Wiedmann, 2014; Hellweg and Canals 2015). For example, Hoekstra and Wiedmann (2014) investigated the global environmental footprint and highlighted several impact categories, such as greenhouse gas (GHG) emissions, water, land, and materials, but they could neither derive the possible relationships among these impact categories nor evaluate the extent of damages in monetary terms. Our results provide the monetary value per unit of damage to the endpoint, and thus, when combined with the findings from previous studies, our results can help the monetary evaluation of an environmental impact at the global scale.

The rest of this paper is organized as follows. Section 2 briefly reviews the survey method and calculation procedures for the MWFs. Section 3 contains details of the estimation results exploring the global and G20 national MWFs. Section 4 extends the analysis to the economic evaluation of environmental impacts on a global scale. Section 5 concludes.

2 Study method

The subjects of the assessment—human health, social assets, biodiversity, and primary production—and research flow have already been described in part 1 of this paper (Itsubo et al. 2015). Therefore, we focus on the calculation procedure for the MWFs. We also briefly review the choice-based experimental design and the discrete choice model used for estimation in this section.

In our survey, the questionnaire provided explanations for the four subjects of assessment and surveyed respondents' perceptions of these subjects.[3] After providing these explanations and conducting a question-and-answer session in order to assist the respondents in evaluating what they value, the respondents were allowed to read the

questionnaire, which posed several hypothetical choice situations as described below. The respondents received a small remuneration for completing the questionnaire. We considered the attributes of environmental policies using the choice experiment method. Based on the reference values (Itsubo et al. 2015), we determined the alternatives, attributes, and attributes levels, as shown in Table 1.

We designed a hypothetical choice set composed of 16 alternatives (8 different choice situations of 2 alternatives) in various combinations of these attribute levels (4 safeguard subjects and environmental tax) using the orthogonal planning method, which is common in choice experimental design and was adopted in a previous study (Itsubo et al. 2012).[4] The attributes of the choice experiment are (1) human health (loss of health per person), (2) social assets (loss of natural resources per person[5]), (3) biodiversity (loss of species on a global scale), (4) primary production (loss of forests on a global scale), and additional tax (yearly per household). We determined these attribute levels using an LCA.[6]

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[3] For the explanation of each subject, see Figure A1 to A4 used in US survey. After each explanation, the respondents were asked about their perceptions of each subject. The ratio of the respondents who replied "very important" to the question "Do you think such a loss of our health (resource, species, and/or forest) is important?" is shown in Table 2.

[4] The orthogonal planning method, which originated in the experimental design field, makes it possible to reduce the number of experiments (questions in the context of this study) significantly and efficiently. This results in minimizing fatigue for the respondents, and maximizes accuracy and information for researchers. In addition, since orthogonal rotation ensures that all components are uncorrelated, multicollinearity can be avoided when estimating the marginal utility of each attribute (Lorenzen and Anderson 1993). In this study, we developed eight patterns of choice sets designed using the orthogonal planning method, and provided the respondent one of the set of eight questions (8 × 2 hypothetical alternatives) at random in order to avoid order effects (see Louviere et al. (2000) for details).

[5] We noted the difficulty faced by the respondents in recalling and (hence valuing) the term "social assets." This has also been observed by several research consulting companies. Thus, we provided an alternate term, "natural resources," with an additional explanation, namely that "natural resources include agricultural products, minerals, fossil fuels, and anything that supports our everyday lives," in order to help participants recall the worth of "aspects valuable to human society."

[6] The reference values in LIME refer to four areas of protection: human health (loss of life expectancy, in DALY (disability adjusted life years)), social assets (loss of assets valuable to human society such as fisheries and agriculture, and forestry, in USD), biodiversity (species extinction, in EINES (expected increase in number of extinct species)), and net primary productivity (inhibited plant growth, in tons). These values are assessed by referring to several public databases such as those of the FAO and IPCC, the USGA's Mineral Commodity Summaries, and reliable previous studies. See Itsubo et al. (2015) for a summary of the current situation of environmental impacts, and Matsuda et al. (2013), Motoshita et al. (2014), Tang et al. (2015a, b), and Yamaguchi et al. (2016) for the detailed assessment process.

In the choice experiment, respondents were asked to choose from three policies; policies 1 and 2 were adjusted for hypothetical situations including environmental improvements and the additional payment of environmental tax, and policy 3 referred to the current situation, with no additional environmental tax. Figure 1 shows an example of one of the choice sets provided in the questionnaire. The status quo option (policy 3) was included in all the questionnaires so that the respondents could always compare and contrast the current and hypothetical situations. All respondents were asked the similar eight questions as shown in Fig. 1.[7]

The questionnaire was translated into the national language of each surveyed country. The values of the environmental tax and social assets were converted into the local currency of the country being surveyed using the relevant purchasing power parity exchange rate (World Bank 2013).[8] The Internet survey and face-to-face interview method were primarily adopted for developed countries and emerging countries, to secure as large a number of samples as efficiently as possible and to minimize survey bias, respectively.[9] Random sampling was implemented for both types of surveys.

We obtained response data from 200 to 250 and 500 to 600 households from each of the emerging and developed countries, respectively.[10]

The response data collected from the survey were statistically analyzed using a random parameter logit model. As already described in part 1 of this paper, the utility function of respondent n choosing alternative i is given by

$$U_{ni} = \beta'_{ns}x_{si} + \beta_m m_i + \beta_0\gamma + \varepsilon_{ni} \qquad (s = \mathrm{HH, SA, BD, PP}) \qquad (1)$$

where x_{si} is an attribute vector for a loss of each safeguard subject s—human health (HH), social assets (SA), biodiversity (BD), and primary production (PP)—of an alternative i, and m_i is a monetary attribute, which is an additional annual environmental tax in this study, as shown in Table 1. The constant γ equals 1 if alternative i is the status quo (the third alternative in this study; see Fig. 1). ε_{ni} is a random term including all effects due to unobservable information of alternative i and respondent n in our survey. Using the maximum simulated likelihood (MSL) method, we can estimate β'_{ns}, a random parameter vector; β_m, a fixed parameter set as a numeraire; β_0, the preference intensity for a loss of each subject; additional environmental tax; and basic utility of the status quo option.[11]

Because β_m indicates the marginal utility of income, marginal willingness-to-pay (MWTP) per household for avoiding a loss of each subject is calculated from the ratio of β_s to β_m, which is given by the following:

$$MWTP_s = \frac{\beta_s}{\beta_m} \quad (s = \mathrm{HH, SA, BD, PP}) \qquad (2)$$

where $MWTP_{HH}$, $MWTP_{SA}$, $MWTP_{BD}$, and $MWTP_{PP}$ denote MWTP per household for avoiding losses of a day, 1 USD worth resources, 1 species, and 100 million tons, respectively.

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[7] We adopted a universal design questionnaire for the respondents from 19 countries who have varied backgrounds (e.g., educational levels, environmental knowledge, and geographic conditions) in order to compare the weighting factors calculated for different regions directly. Since we obtained this major contribution in exchange for adapting to specific local situations, the surveys were carefully implemented through multiple amendment stages such as back-translation, consulting with local research companies, and several pretests.

[8] We first set the initial value of the tax as 100 ~ 300 USD after referring to previous environmental valuation studies. Then, we adjusted the values to each local currency using the PPP conversion factor. After consulting a local research company and conducting several pretests, we amended the level of this attribute as needed. For example, a large majority of respondents choosing the status quo option with no additional tax in many choice situations is a sign of a very high tax. In such cases, we have to amend the tax level to make it more reasonable.

[9] In developed countries, where the internet diffusion rates and familiarity with environmental policies are relatively high, respondents replied to the questionnaire provided online in HTML format. In emerging countries, where familiarity with the internet and environmental tax are relatively low, trained interviewers visited each respondent's house and explained the questionnaire to him/her in detail before obtaining the answers. The internet diffusion rates prevailing during the course of our study were as follows: Japan (90%), United Kingdom (90%), Canada (86%), Korea (85%), United States (85%), Australia (83%), Germany (84%), France (82%), Russian Federation (68%), Saudi Arabia (61%), Argentina (60%), Italy (59%), Brazil (51%), South Africa (47%), Turkey (46%), China (46%), Mexico (44%), India (15%), and Indonesia (15%) (ITU 2013). Traditionally, face-to-face interviews are usually preferable (Arrow et al. 1993). However, according to recent studies that examined sample representativeness and hypothesis bias among internet users, internet-based contingent valuation (CV) surveys provide results similar to those of face-to-face surveys (Neilsen 2011). In addition, Olsen (2009) conducted a choice experiment study and reported no significant differences in the unconditional WTP estimates in spite of differences in demographics between the internet and traditional mail survey modes. With the rapid growth in the number of users, the internet has become a valuable tool for non-market valuations that place priority on receiving valid replies and higher response rates. See Meyerhoff et al. (2014) as an example of a recent comprehensive study exploring the effects of respondent and survey characteristics and internet survey mode effects through a meta-analysis.

[10] After answering the eight choice questions, the respondents who chose policy 3 (status quo) for every choice situation faced an additional choice; they were requested to select what they perceived to be the most appropriate reason for preferring the status quo option from among the following: (1) I cannot afford the large amount of tax, (2) I am not interested in environmental problems, (3) I am not sure that my own opinions are reflected in the actions, (4) People in other regions should bear the responsibility, (5) There is no need to pay a tax for such actions, (6) I made this choice for religious reasons, and (7) I cannot trust the information provided. To conduct the estimation using reliable response data, we excluded the response data of respondents who selected answers (3)–(7) as their protest responses. See Arrow et al. (1993) for recommendations pertaining to eliminating protest responses.

[11] It is naturally acceptable to assign $\beta_0 = 0$ if the respondents have no basic preference for the status quo. While $\beta_0 = 0$ for LIME2 (Itsubo et al. 2012), it is more appropriate to assign $\beta_0 \neq 0$ for some countries in this study because of those statistical significance. The MSL method and estimation procedures are described in detail in part 1 (Itsubo et al. 2015). Louviere et al. (2000) give a technical account of the choice model.

The MWFs of each subject are defined as follows:

$$\text{MWF}_{Human\ health} = MWTP_{\text{HH}} \cdot \frac{F}{D} \cdot 365 \qquad (3)$$

$$\text{MWF}_{Social\ assets} = MWTP_{\text{SA}} \cdot \frac{F}{D} \qquad (4)$$

$$\text{MWF}_{Biodiversity} = MWTP_{\text{BD}} \cdot F \qquad (5)$$

$$\text{MWF}_{Primary\ production} = MWTP_{\text{PP}} \cdot F \qquad (6)$$

where F denotes the global number of households, and D denotes the global population.[12] Therefore, the monetary value per unit of damage to each safeguard subject, namely, year, USD, species, and 100 million tons, respectively, is obtained as the corresponding MWF in this study.[13]

3 Results and discussion

3.1 Respondents' perceptions

Table 2 shows respondents' perceptions with respect to the importance of each safeguard subject. The respondents in G8 countries tend to view biodiversity (67.2%) and primary production (74.3%), which are the constituents of the ecosystem, as more important, rather than human health (49.7%) and social assets (49.0%), which are the constituents of human society. On the other hand, the majority of respondents from the emerging G20 countries perceive all these losses as very important, with the highest priority being accorded to human health (80.2, 69.6, 74.9, and 77.9%, respectively). In addition, variances in responses between the emerging G20 countries are generally larger than the corresponding values for the G8 countries' respondents.

We also asked the respondents to choose what they perceived to be the most serious problem from among the following 10 alternatives: global warming, unsafe drinking water and lack of sanitary facilities, air pollution, insufficient water supply, diminishing natural resources due to the consumption of minerals and fossil fuels, deforestation, land exploitation or development, unemployment, lack of education, and the rights of women and children. Global warming was considered to be the most serious problem of all for the G8 countries' respondents, followed by unsafe drinking water and lack of sanitary facilities. A relatively large number of the respondents from the other emerging countries chose air pollution as either the most or the second most serious problem.

3.2 Estimation results

3.2.1 Preference intensities

Table 3 displays the estimation results using utility function (1) for the G20, G8, G20 excluding G8, and each of the G20 countries. The number of respondents in the G20, G8, and G20 excluding G8 countries is 6183, 4146, and 2037, respectively. The corresponding log likelihood ratios are 0.47, 0.45, and 0.51, all of which are sufficiently high for the discrete choice model.[14,15] We assumed that the parameters are distributed normally. The mean and standard deviation values are reported, except for an environmental tax that is set as a numeraire. "Yes" is displayed with its direction in the column "Status quo" if β_0 is statistically significant, and "No" is displayed otherwise.

First, the estimated preference intensities of all four subjects are statistically significant and negative at the 1% level, since utility decreases as a result of increased damage. The parameters of environmental tax are also negative and statistically significant at the 1% level in every area except Mexico (listed in *italics*). All the estimates for the status quo parameter are negative, thus indicating that, on average, the respondents prefer an improvement over the current status in these countries.

3.2.2 Monetary weighing factors

Table 4 shows the MWFs calculated using the results in Table 3 and Eqs. (2) to (6). According to the estimates

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[12] For our calculations, we used 1,794,600,980 as the global number of households and 7,052,000,000 as the global population for calculations (UN Demographic Yearbook 2010).

[13] We can obtain other MWFs of the social assets equivalents, MWF^{SA}, defined as follows for each subject:

$$\text{MWF}^{SA}_{Human\ health} = \frac{\beta_{\text{HH}}}{\beta_{\text{SA}}} \cdot 365 \quad (F1)$$

$$\text{MWF}^{SA}_{Social\ assets} = \frac{\beta_{\text{SA}}}{\beta_{\text{SA}}} \quad (F2)$$

$$\text{MWF}^{SA}_{Biodiversity} = \frac{\beta_{\text{BD}}}{\beta_{\text{SA}}} \cdot D \quad (F3)$$

$$\text{MWF}^{SA}_{Primary\ production} = \frac{\beta_{\text{PP}}}{\beta_{\text{SA}}} \cdot D \quad (F4)$$

Because β_{SA} indicates the marginal utility in USD of social assets equivalents per person, the monetary value of social assets equivalents per unit of damage to each safeguard subject is obtained as the alternative MWF. The basic MWFs (evaluated based on environmental tax) are consistent with the value of WTP used in general economic valuation studies, while the alternative MWFs (evaluated based on social assets) are useful for integrating the damage to the four safeguard subjects into a single index. Although the alternative MWFs of social assets equivalents (MWF^{SA}) have been adopted previously (LIME2, Itsubo et al. 2012), this study prioritized the use of the basic MWFs to maintain consistency with general economic valuation studies. To compare these representative values, see Table 6.

[14] The likelihood ratio index (LRI) is defined as LRI = $1-(L_1/L_0)$, where L_1 and L_0 denote the natural log of maximum likelihood of our model (SLL (simulated log likelihood) in formula (11) of Itsubo et al. (2015)) and that of the null model with all $\beta = 0$ except β_0 (an intercept), respectively. LRI ranges from 0 to 1, and 0.2 are sufficiently high for a discrete choice model. LRI is also known as McFadden's pseudo R-squared, which is used to evaluate the goodness-of-fit of logistic models. See McFadden (1974) for details.

[15] The LRI for Saudi Arabia is extraordinarily high, exceeding 0.9. This means that the majority of the respondents provided similar answers in the choice experiments. According to a local research company, the field survey was carefully monitored, which is evident from the careful records of serial numbers, age groups, etc. We thus attributed this result to domestically similar preferences among Saudi Arabian respondents with respect to these four safeguard subjects with some speculation that a strong bias might have existed at the time the survey was conducted.
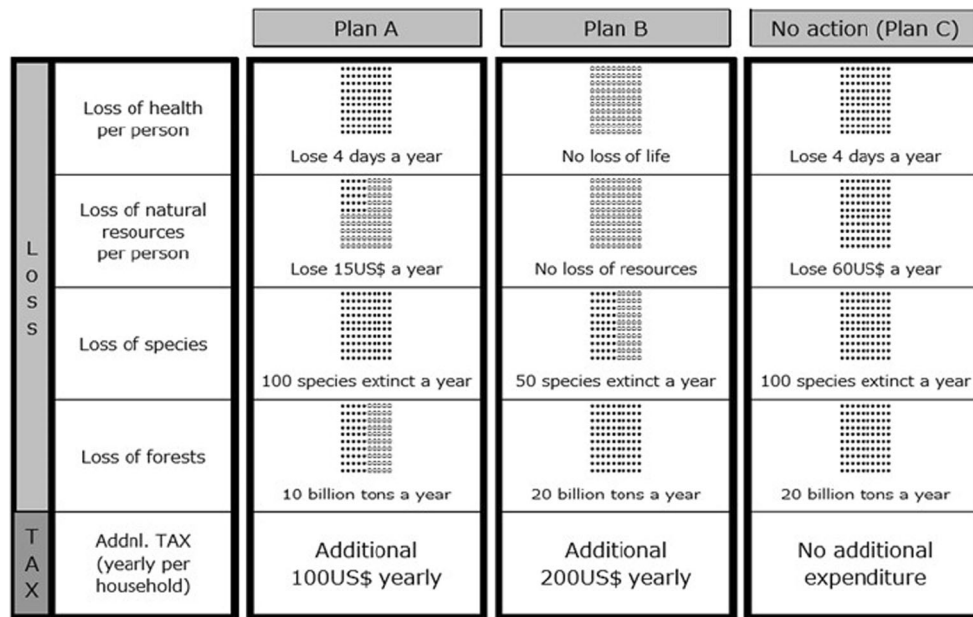
Fig. 1 An example of the profiles used in this study. Note: Instead of using quantitative values such as fractional numbers, we adopted visual aids in order to improve respondents' understanding of possible changes in the four areas of protection as defined by LIME. Before undertaking the choice experiment, we explained to the respondents that the *black dots* indicate the degree of loss; the higher the number of *black dots*, the greater the degree of loss. Visual aids are used as risk communication tools and can facilitate the understanding of relatively small risks in the context of health. We selected icon arrays (shown in this figure) from among a variety of tools, such as risk ladders and pie charts. Loomis and duVair (1993) evaluated the effect of visual aids on WTP. For additional details about the application of visual aids, see Lipkus and Holland (1999), Okan et al. (2012), and Garcia and Cokely (2013)

obtained using the pooled data of all G20 countries, the MWFs are 10,000 USD for human health (per year), 0.77 USD for social assets (per USD of resources), 6.6 billion USD for biodiversity (per species), and 3.1 billion USD for primary production (per 100 million tons). Similarly, 7300 USD for human health, 0.47 USD for social assets, 6.3 billion USD for biodiversity, and 2.8 billion USD for primary production are obtained as the MWFs for the developed G8 countries. All the results are lower than the corresponding values of the emerging countries: 20,000 USD for human health (2.7 times), 1.7 USD for social assets (3.6 times), 7 billion USD for biodiversity (1.1 times), and 3.7 billion USD for primary production (1.3 times). These gaps are particularly prominent in the MWFs of human health and social assets, while a small difference exists between the MWFs of biodiversity and primary production. The results based on the pooled data indicate that the loss of health and social assets are perceived as more urgent and crucial in the emerging countries relative to the developed G8 countries.

Table 4 also shows country-specific MWFs.[16] For the developed countries, the MWFs of human health range from

2900 USD (USA) to 16,000 USD (Italy), and the corresponding values for the emerging countries are 6700 USD (Russia) to 84,000 USD (Argentina). This result is consistent with the dimensionless weighting factors calculated in part 1 of this paper. The health of residents constitutes one obvious difference between the developed and emerging countries. Respondents from emerging countries tend to suffer poor health because of environmental problems, such as air pollution, as described in Table 2. This constitutes an immediate threat, which, conversely, is already restricted to some extent in developed countries.

The MWFs of social assets range from 0.08 (USA) to 0.95 (Italy) in the developed countries, and from 0.71 (Brazil) to 11 (Argentina) in the emerging countries. This result indicates that the respondents in developed countries evaluate social assets with some discount, while those in emerging countries place more value on social assets than their private income. This viewpoint may arise because, unlike the respondents in emerging countries, those from developed countries perceive social assets to be substitutable by other technologies and international trade in exchange for money.

The MWFs of biodiversity range from 1.7 billion USD (USA) to 11 billion USD (Italy) in developed countries, and from 3.4 billion USD (Brazil) to 19 billion USD (Argentina) in emerging countries. The MWFs of primary production range from 810 million USD (USA) to 4.8 billion USD (Italy) in developed countries, and from 1.9 billion USD

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[16] The MWFs could not be calculated for Mexico because of the insignificance of the numeraire parameter of environmental tax. In addition, among the G8 countries, the all values for Italy are generally larger than those for the other countries in the group. Because the internet diffusion rate is considerably low in Italy (59%) although it is a developed country, there is possibly some upper bias in the online response data from Italy.

Table 2 Respondents' perceptions of safeguard subjects and environmental problems

	The ratio of the respondents who think a loss of each safeguard subject very important[a]				The most serious problem and ratio (%)[b]	
	Human health	Social assets	Biodiversity	Primary production	1st	2nd
G8 average (SD of national means)	49.7	49.0	67.2	74.3		
	(13.4)	(8.8)	(6.9)	(5.8)		
USA	58.2	53.1	63.6	70.5	GW 27	UE 22
Canada	58.6	54.0	68.7	75.8	GW 28	WS 16
Australia	50.1	46.7	68.8	71.3	GW 30	WS 13
Germany	30.6	41.7	69.8	80.0	GW 30	DF 12
UK	57.0	55.0	68.4	75.2	GW 25	WS 18
France	48.2	48.0	68.9	76.3	GW 28	WS 17
Japan	29.0	32.8	52.8	63.5	GW 41	WS 11
Italy	65.8	60.7	77.0	81.9	GW 23	AP 20
G20 excl G8 average (SD of national means)	80.2	69.6	74.9	77.9		
	(20.7)	(23.9)	(21.0)	(22.7)		
Korea	48.0	44.5	57.5	62.0	GW 64	AP 9
Argentina	93.5	88.0	95.0	94.5	GW 33	AP 18
Saudi Arabia	87.0	38.5	29.5	23.0	AP 26	UE 18
Russia	46.0	33.5	55.0	60.0	AP 40	DF 14
Mexico	95.5	90.0	95.5	98.5	GW 36	WS 13
Turkey	84.0	78.0	91.5	95.5	GW 32	ED 19
Brazil	94.5	86.5	90.0	86.5	GW 27	WS 17
South Africa	89.5	77.0	72.5	81.5	UE 46	GW 22
China	52.0	45.0	66.5	71.5	GW 31	AP 29
Indonesia	99.0	93.5	82.0	95.0	UE 28	GW 28
India	93.0	91.4	88.8	89.3	WS 27	AP 20

[a] The ratio of the respondents who replied "very important" to the question, "Do you think such a loss of our health (resources, species, and/or forest) is important?"

[b] The respondents were asked what they believed was the most serious problem from among the following 10 alternatives: *GW* (global warming), *WS* (unsafe drinking water and lack of sanitary facilities), *AP* (air pollution), insufficient water supply, diminishing natural resources resulting from the consumption of minerals and fossil fuels, *DF* (deforestation), land exploitation or development, *UE* (unemployment), *ED* (lack of education), and the rights of women and children

(Brazil) to 11 billion USD (Argentina) in emerging countries. In contrast to the dimensionless weighting factors calculated in part 1 of this paper, two subjects related to the ecosystem are negatively, although weakly, correlated with individual income levels.[17]

3.2.3 Cross-country heterogeneity

Regarding the standard deviations, there is considerably greater variation in the emerging countries for all subjects. These variations are approximately 6 times (human health), 12 times (social assets), and more than double (biodiversity and primary production) the corresponding values in developed countries. For two subjects related to human society, the variations in the MWFs are quite small within the developed countries but considerably large among the emerging countries. This finding indicates that while the MWFs related to human society, namely, human health and social assets, are internationally transferable within developed countries, caution must be exercised while considering such transfers among emerging countries or between developed and emerging countries. Moreover, the variations in the MWFs of biodiversity and primary production, which are related to the ecosystem, are considerably large in both developed and emerging countries. Thus, these MWFs must be used judiciously when considering international transfers even within developed countries.

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[17] Based on the statistics GDP per capita (PPP, current international USD) from World Bank (2013).

Table 3 Preference intensities for the four subjects and environmental tax

	Number of samples	LRI	Preference intensity				Tax	Status quo
			Human health	Social assets	Biodiversity	Primary production		
G20	6183	0.47	−6.3.E−01	−1.7.E−02	−2.1.E−02	−9.8.E−03	−5.7.E−03	Yes
			(7.1E−01)	(2.2E−02)	(2.0E−02)	(8.9E−03)		−
G8	4146	0.45	−5.5.E−01	−1.3.E−02	−2.5.E−02	−1.1.E−02	−7.0.E−03	Yes
			(6.8E−01)	(1.7E−02)	(2.3E−02)	(1.0E−02)		−
G20 excluding G8	2037	0.51	−8.1.E−01	−2.5.E−02	−1.5.E−02	−7.8.E−03	−3.8.E−03	Yes
			(7.8E−01)	(2.9E−02)	(1.3E−02)	(6.6E−03)		−
Country specific								
USA	483	0.47	−6.8.E−01	−7.1.E−03	−2.1.E−02	−9.9.E−03	−2.2.E−02	Yes
			(6.9E−01)	(9.3E−03)	(1.8E−02)	(9.5E−03)		−
Canada	543	0.47	−6.7.E−01	−2.3.E−02	−2.2.E−02	−1.1.E−02	−9.8.E−03	Yes
			(8.6E−01)	(2.8E−02)	(2.3E−02)	(1.0E−02)		−
Australia	484	0.45	−4.7.E−01	−1.7.E−02	−2.7.E−02	−1.0.E−02	−7.7.E−03	Yes
			(5.6E−01)	(2.5E−02)	(2.6E−02)	(9.8E−03)		−
Germany	509	0.46	−3.3.E−01	−1.8.E−02	−2.8.E−02	−1.3.E−02	−6.3.E−03	Yes
			(4.5E−01)	(2.0E−02)	(2.3E−02)	(1.0E−02)		−
UK	515	0.50	−6.4.E−01	−2.4.E−02	−2.6.E−02	−1.2.E−02	−9.0.E−03	Yes
			(7.2E−01)	(3.5E−02)	(2.4E−02)	(1.0E−02)		−
France	508	0.43	−5.1.E−01	−1.7.E−02	−2.2.E−02	−1.1.E−02	−5.9.E−03	Yes
			(6.8E−01)	(2.5E−02)	(2.3E−02)	(9.8E−03)		−
Japan	591	0.46	−3.9.E−01	−2.1.E−02	−2.5.E−02	−1.3.E−02	−1.1.E−02	Yes
			(6.7E−01)	(3.0E−02)	(2.5E−02)	(1.2E−02)		−
Italy	513	0.50	−7.0.E−01	−1.5.E−02	−2.4.E−02	−1.1.E−02	−4.1.E−03	No
			(6.4E−01)	(1.4E−02)	(2.4E−02)	(8.9E−03)		−
Korea	184	0.42	−4.9.E−01	−1.9.E−02	−1.4.E−02	−8.9.E−03	−6.7.E−03	Yes
			(6.9E−01)	(4.1E−02)	(2.3E−02)	(1.0E−02)		−
Argentina	195	0.66	−1.1.E+00	−5.1.E−02	−1.2.E−02	−7.5.E−03	−1.2.E−03	No
			(4.4E−01)	(3.2E−02)	(2.7E−04)	(9.8E−04)		−
Saudi Arabia	200	0.92	−4.5.E+00	−7.9.E−02	−6.6.E−02	−3.6.E−02	−9.9.E−03	No
			(1.1E+00)	(1.7E−02)	(5.9E−04)	(4.5E−04)		−
Russia	177	0.40	−4.0.E−01	−1.8.E−02	−1.6.E−02	−7.0.E−03	−5.6.E−03	Yes
			(7.7E−01)	(4.0E−02)	(1.9E−02)	(6.8E−03)		−
Mexico	167	0.49	−5.6.E−01	−2.9.E−02	−1.5.E−02	−8.4.E−03	−1.8.E−04	No
			(6.1E−01)	(2.5E−02)	(1.5E−02)	(7.3E−03)		−
Turkey	191	0.51	−7.5.E−01	−3.5.E−02	−2.2.E−02	−9.1.E−03	−2.5.E−03	Yes
			(8.1E−01)	(4.6E−02)	(2.9E−02)	(9.2E−03)		−
Brazil	182	0.39	−6.1.E−01	−1.5.E−02	−1.0.E−02	−5.8.E−03	−5.5.E−03	Yes
			(6.4E−01)	(2.4E−02)	(4.6E−03)	(5.2E−03)		−
South Africa	179	0.46	−8.1.E−01	−2.0.E−02	−1.2.E−02	−6.3.E−03	−3.1.E−03	No
			(7.6E−01)	(2.7E−02)	(1.2E−02)	(5.8E−03)		−
China	199	0.53	−4.1.E−01	−1.9.E−02	−1.3.E−02	−5.8.E−03	−1.6.E−03	Yes
			(3.7E−01)	(1.4E−02)	(2.2E−03)	(8.3E−04)		−
Indonesia	176	0.54	−6.3.E−01	−1.6.E−02	−6.9.E−03	−7.2.E−03	−2.3.E−03	Yes
			(4.7E−01)	(1.3E−02)	(8.1E−03)	(1.5E−03)		−
India	187	0.68	−9.0.E−01	−3.3.E−02	−1.9.E−02	−1.0.E−02	−2.4.E−03	No
			(3.1E−01)	(1.6E−02)	(5.8E−04)	(1.5E−04)		−

This table shows the estimation results of average preference intensities and standard deviations (given in *parentheses*), using utility function (1) for the G20 countries. LRI is the likelihood ratio index, defined as LRI $= 1 − (L_1/L_0)$, where L_1 and L_0 denote the natural log of the maximum likelihood of our model and that of the null model with all $\beta = 0$ except β_0 (an intercept), respectively. "Yes" in the column "status quo" indicates that the preference intensities for the current status are significantly different from zero and negative in all concerned countries. All parameters are statistically significant at the 1% level, except for environmental tax in Mexico and several standard deviations (written in *italics* if insignificant)

3.2.4 Population-weighted MWFs

As described above, the MWFs estimated using the pooled data are useful for an overview of the data; nevertheless, they are highly influenced by the composition of the sample. Table 5 shows the population-weighted averages of the estimated factors of each G20 country after adjustment according to the current population statistics (World Bank 2013). For MWFs based on environmental tax, each population-weighted average of the MWFs (23,000 USD for human health, 2.5 USD for social assets, 11 billion USD for

Tabl 4 Weighting factors expressed in monetary values

Monetary weighting factors (USD)

	Human health (1 year)	Social assets (1 USD)	Biodiversity (1 species)	Primary production (100 million tons)
G20 (WF$_{G20}$)	1.0.E+04	7.7.E−01	6.6.E+09	3.1.E+09
G8 (WF$_{G8}$)	7.3.E+03	4.7.E−01	6.3.E+09	2.8.E+09
G20 excluding G8 (WF$_{G20excG8}$)	2.0.E+04	1.7.E+00	7.0.E+09	3.7.E+09
Country specific				
USA (WF$_{USA}$)	2.9.E+03	8.3.E−02	1.7.E+09	8.1.E+08
Canada (WF$_{CAN}$)	6.4.E+03	6.0.E−01	4.0.E+09	2.0.E+09
Australia (WF$_{AUS}$)	5.7.E+03	5.6.E−01	6.4.E+09	2.4.E+09
Germany (WF$_{DEU}$)	4.9.E+03	7.4.E−01	8.0.E+09	3.6.E+09
UK (WF$_{GBR}$)	6.6.E+03	6.7.E−01	5.2.E+09	2.5.E+09
France (WF$_{FRA}$)	8.0.E+03	7.1.E−01	6.8.E+09	3.3.E+09
Japan (WF$_{JPN}$)	3.3.E+03	4.9.E−01	4.1.E+09	2.2.E+09
Italy (WF$_{ITA}$)	1.6.E+04	9.5.E−01	1.1.E+10	4.8.E+09
Korea (WF$_{KOR}$)	6.8.E+03	7.4.E−01	3.7.E+09	2.4.E+09
Argentina (WF$_{ARG}$)	8.4.E+04	1.1.E+01	1.9.E+10	1.1.E+10
Saudi Arabia (WF$_{SAU}$)	4.2.E+04	2.0.E+00	1.2.E+10	6.6.E+09
Russia (WF$_{RUS}$)	6.7.E+03	8.2.E−01	5.1.E+09	2.2.E+09
Mexico (WF$_{MEX}$)	NA	NA	NA	NA
Turkey (WF$_{TUR}$)	2.8.E+04	3.6.E+00	1.6.E+10	6.6.E+09
Brazil (WF$_{BRA}$)	1.0.E+04	7.1.E−01	3.4.E+09	1.9.E+09
South Africa (WF$_{ZAF}$)	2.5.E+04	1.6.E+00	7.1.E+09	3.7.E+09
China (WF$_{CHN}$)	2.4.E+04	3.0.E+00	1.5.E+10	6.5.E+09
Indonesia (WF$_{IDR}$)	2.5.E+04	1.8.E+00	5.3.E+09	5.5.E+09
India (WF$_{IND}$)	3.5.E+04	3.6.E+00	1.4.E+10	7.6.E+09
SD of the mean WFs among				
G8	4.1.E+03	2.5.E−01	2.8.E+09	1.2.E+09
G20 excluding G8	2.3.E+04	3.1.E+00	5.7.E+09	3.0.E+09

This table shows the MWFs of human health (year), social assets (in USD of resources), biodiversity (species), and primary production (100 million tons). *NA* not available, because of insignificance of the monetary parameter for Mexico

biodiversity, and 5.6 billion USD for primary production) is larger than the results obtained using the simply pooled data by giving more weightage to the preferences of respondents from the emerging countries. In addition, the differences between the values of the developed and emerging countries become larger (5200

Table 5 Summary of the population-weighted monetary weighting factors obtained in this study

Monetary weighting factors (USD)

	Human health (1 year)	Social assets (1 USD)	Biodiversity (1 species)	Primary production (100 million tons)
MWFs				
G20 (WF$_{G20, weighted}$)	2.3.E+04	2.5.E+00	1.1.E+10	5.6.E+09
G8 (WF$_{G8, weighted}$)	5.2.E+03	4.3.E−01	4.4.E+09	2.1.E+09
G20 excluding G8 (WF$_{G20excG8, weighted}$)	2.7.E+04	2.9.E+00	1.3.E+10	6.3.E+09

This table presents the population-weighted averages of the estimated MWFs for each G20 country, the G8 countries, and other emerging countries

Fig. 2 **a** Global-scale and country-specific MWFs related to human society. **b** Global-scale and country-specific MWFs related to the ecosystem
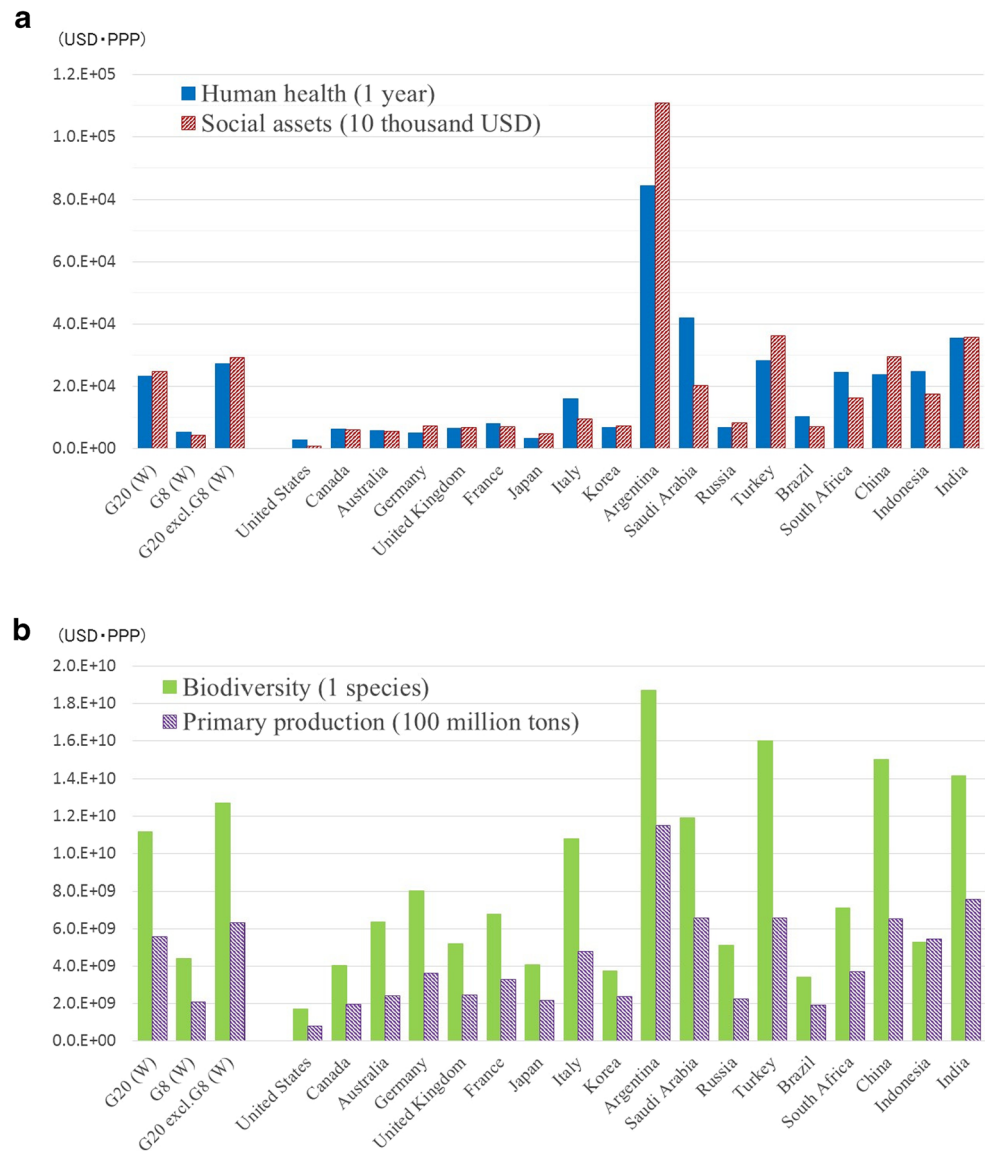
USD, 0.43 USD, 4.4 billion USD, and 2.1 billion USD in developed countries, and 27,000 USD, 2.9 USD, 13 billion USD, and 6.3 billion USD in emerging countries, respectively) when considering weighted MWFs. Figure 2a, b shows the representative values of this study, which are global-scale and country-specific MWFs related to human society and the ecosystem, respectively.

3.3 Comparison with previous studies and validity of our results

3.3.1 Results of Japanese respondents in LIME2

In order to compare this study's results with those of LIME2 (Itsubo et al. 2012), Table 6 shows the reference values and MWFs of the two studies. First, note that the questionnaire

used for the current study provided the respondents with the reference values of damages on a global scale, while the national reference values for Japan were provided in the LIME2 questionnaire. The global reference values reflect damages that have occurred at locations relatively far away from the respondents, while the national reference values reflect the damages (half of which originated in Japan in LIME2) that have occurred closer to home (i.e., Japan). The reference values corresponding to each damage event are 4 days per person annually (double that in LIME2), 60 USD per person annually (less than one-third of 200 USD in LIME2), 100 species in the world annually (100 times the corresponding value in LIME2), and 20 billion tons in the world annually (100 times the corresponding value in LIME2).

Next, because the parameter of social assets—another monetary parameter—was set as the numeraire in LIME2 and the basic statistics (i.e., population) used are at the

Table 6 Comparison between LIME2 and LIME3—the results of Japanese respondents

Year			LIME2 (Itsubo et al. 2012) 2005		LIME3 (this study)2013	
Reference values[a] (the respondents faced in questionnaire)		HH	2	Day/p/year	4	Day/p/year
		SA	200	USD/p/year	60	USD/p/year
		BD	1	Species/national/year	100	Species/world/year
		PP	0.1	%/national/year[f]	10	Times/world/year[f]
			2	(100 mil.t./national/year)	200	100 mil.t./world/year
MWFs (USD)[b]						
Global scale[d]	Value per person	HH	4.4.E+03	1 DALY (year)/p	*3.3.E+03*	1 DALY (year)/p
	Value per person	SA	3.4.E−02	1 USD/p	*4.9.E−01*	1 USD/p
	National total value	BD	2.4.E+11	1 EINES/world	*4.1.E+09*	1 EINES/world
	National total value	PP	7.7.E+10	100 mil.t./world	*2.2.E+09*	100 mil.t./world
MWFs (USD of social assets equivalent)[b,c]						
National scale[e]	Value per person	HH	*1.3.E+05*	1 DALY (year)/p		
	Value per person	SA	*1.0.E+00*	1 USD/p		
	National total value	BD	*1.3.E+11*	1 EINES/national		
	National total value	PP	*4.1.E+10*	100 mil.t./world		

Italic numbers are the representative values of each study

HH human health, *SA* social assets, *BD* biodiversity, *PP* primary production

[a] Reference values are derived by the LCIA method

[b] 1 USD = 112.3 JPY (PPP, current international USD in 2013 (World Bank))

[c] The representative values of LIME2 are calculated using Eqs. (F1) to (F4) in footnote 18

[d] World total population and number of households are 7,052,000,000 and 1,794,600,980, respectively

[e] Japan's total population in LIME2 is 127,800,000

[f] Proportion to the total forest in Japan

national scale, we recalculated the global-scale MWFs defined above based on the results of LIME2 so that we may compare the MWFs estimated using the data of the Japanese respondents in our study. The values are generally less than those of LIME2, except for social assets. For MWFs based on environmental tax, the MWFs are 3300 USD a day per person (three-quarters of 4400 USD), 0.49 USD for 1 USD worth per person (differs by one order of magnitude from 0.03 USD), 4.1 billion USD for one species (differs by two orders of magnitude from 240 billion USD), and 2.2 billion USD for 100 million tons (differs by one order of magnitude from 77 billion USD).

For the loss of human health, the world and national averages were presented to the respondents in our questionnaire and for LIME2, respectively. Our pre-survey and interview data obtained before the main large-scale survey indicated that Japanese respondents perceived their health risks to be lower than the world average. This fact led to lower MWFs in our study even though they evaluated the same subjects. Regarding the loss of social assets, the MWFs of LIME2 are significantly small (0.03 USD). Note that the subjects evaluated are inherently different, namely, the loss of resources in the world in the current study and the loss of resources in Japan alone in LIME2. This fact indicates that Japanese respondents probably place more value on the global-scale loss

of mineral and fossil resources. This interpretation is consistent with the fact that Japan lacks such resources and relies heavily on resources imported from other countries. Another possible reason of the noticeable difference between the MWFs of social assets is the growing interest in mineral and fossil resources in Japan from 2005 to 2013.[18]

Regarding the loss of biodiversity and primary production, note that the respondents of the two studies were provided

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[18] The different composition of types of depleted resources could be another cause for the variation in the MWFs of social assets between the two studies. For example, the major cause of the loss in our study is consumption of fossil and mineral fuels, while it is global warming in LIME2. In our study, the causes for the loss were denoted by a combination of fossil fuel consumption and mineral fuel consumption (65% and 35%, respectively, as shown in Fig. A2). The major cause of this loss of natural resources is "the impact on future generations due to consumption and depletion of fossil fuels." Apart from these causes, the natural resources that our grandchildren and descendants should receive are also dwindling from "consumption and depletion of minerals fuels." In LIME2, on the other hand, the causes of the loss included a combination of global warming, consumption of fossil fuels, consumption of mineral fuels, soil acidification, photochemical smog, and eutrophication (53, 19, 12, 13, 2, and 1%, respectively). The major cause of the loss is global warming, due to which more land is being lost to submergence below the sea level, leading to decreasing harvests of agricultural and marine products. Apart from these, our social assets are also dwindling from the consumption of minerals and fossil fuels, as well as soil acidification.

Table 7　Economic values related to losses in the four subjects

	Unit	This study	Previous studies		
			Values	Original unit	Authority/Study
Human health[a]	1 year (USD)	2.3.E+04	2.3.E+05	VSL	USDOT
			2.1.E+05	VSL	USEPA
			6.8.E+04	VSL	UKDFT
			4.8.E+04 ~ 9.6.E+04	VSL	European Commission
			1.0.E+05	YOLL	EPS
			4.8.E+04	VOLY	NEEDS/ExternE
Social assets[b]	1 USD (USD)	2.5.E+00	–	–	–
Biodiversity[c]	1 species (USD)	1.1.E+10	3.9.E+11	Water fringe	Mitani and Kuriyama (2005)
			3.9.E+10	Cheirotonus jambar	Yoshida (2013)
			1.6.E+10	Wild cat (median)	MOEJ (2014)
			4.5.E+10	Wild cat (mean)	MOEJ (2014)
Primary production[d]	100 million tons (USD)	5.6.E+09	7.0.E+10	Tropical forests	TEEB (2009)
			1.6.E+10	Other forests	TEEB (2009)
			1.6.E+10	Woodland/Shrubland	TEEB (2009)
			1.0.E+10	Grasslands	TEEB (2009)

[a] The values shown represent the economic values of 1 year's loss of life. VSL estimates have been converted to VSLY using Eq. (7)

[b] No comparative values for social assets are available in the literature

[c] All figures have been converted to show the world total value for one species. We referred to Mitani and Kuriyama (2005) and adjusted the values from 2005 to 2013 prices using the PPP conversion factor at that time and the US CPI because their survey was conducted a decade ago

[d] All figures in TEEB (2009) have been converted to show the world total value of 100 million tons, assuming annual average plant growth per hectare as 10 tons

different information pertaining to these damages. The Japanese respondents evaluated the global-scale environmental damage in the current study and domestic environmental damage in LIME2. The trend that the respondents are willing to pay more for local environmental conservation than for conservation in foreign countries has also been observed in a previous study on environmental economic valuation (Lindhjem et al. 2011, Tsurumi et al. 2015). For the respondents, WTP for biodiversity differs according to the location of the problem. In addition, the MWFs at the national scale, which are the representative values of LIME2, appear in the last four rows for reference.[19]

3.3.2 Previous economic valuation studies

The results of previous studies on the economic evaluation of the four subjects except for social assets, which have no comparative values, are listed in Table 7. For consistency, all the figures have been converted to show the values for 1 year's loss of life for human health, one species for biodiversity, and 100 million tons for primary production.

Value of statistical life (VSL) estimates are widely used by many US and European agencies, such as US Department for

Transportation (DOT), the US Environmental Protection Agency (EPA), UK Department for Transportation (DFT), and European Commission, in policy assessments pertaining to mortality risk reduction. For comparison, these values are converted into Value of Statistical Life Year (VSLY), given by[20]

$$VSLY = \frac{VSL}{\left(1-(1+r)^{-L}\right)\Big/r} \tag{7}$$

where L is the remaining lifetime (assumed to be 40 in Table 7), and r is the rate at which the utility is discounted (assumed to be 0 in Table 7). Though it is inappropriate to make a simple comparison with the results of our study (because the values of VSL employed by these official agencies are mainly based on wage risk and road safety studies using private market data), we observe that these values are larger than the results of our study.

VSL estimates from various studies show a wide range, from 7292 USD to 86.3 million USD, with median 2.4 million USD, depending on the risk valuation context such as cause of

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[19] These values are calculated using equations (F1) to (F4) in footnote 18.

[20] For recent introduction of VSL and VSLY, see Hammitt (2000) and Lindberg (2015) for examples.

death (e.g., traffic accident, wage risk, cancer, other illness, and environment-related), immediate or future risk, change in public or private risk, and small or large risk reduction (Lindhjem et al. 2011).[21] The information regarding loss of health in our questionnaire can be specified as environment-related, latent, public risk, and small change in risk (4 days annually), and all these contexts cause smaller mortality values (Arberini and Scasny 2011; Lindhjem et al. 2011). For other LCA methodologies, 100,000 USD per year of lost life (YOLL), adopted in EPS derived from previous VSL estimates, is also reasonably larger than the result of our study.[22] NEEDS, which is proximate to the subject evaluated in our study in terms of methodology and the definition of mortality, employs 48,000 USD as the mean value of the increase in life expectancy.[23] In the context of public programs using interview data, our study and NEEDS share the same idea of life expectancy evaluation, but the scales of such impacts differ (national in NEEDS and global in LIME), leading to smaller values in our study. This interpretation is consistent with our result showing smaller values for developed countries, where the respondents have a relatively lower baseline risk perception than those in emerging countries.

WTP for avoiding extinction of a species has been estimated by several studies. Table 7 shows the comparable values calculated based on the results of previous studies and world statistics. While these studies commonly evaluated accessible local species such as water fringe, *cheirotonus jambar*, and the iriomote wild cat (Mitani and Kuriyama 2005; Yoshida 2013; MOEJ 2014, respectively), we evaluate abstract species present in locations relatively far away from the respondents and on the global scale. This difference in approach leads to somewhat smaller values for our study.

For primary production, TEEB (2009) estimates the potential benefits of several biomes, including forests, based on the results of 104 case studies (507 values). Assuming average yearly plant growth per hectare as 10 ton, the comparable values can be calculated as shown in Table 7. As is the case with biodiversity, the respondents in the studies commonly evaluated biomes close to their respective habitations, thus explaining the relatively smaller values in our study.

The MWFs of our study are generally smaller as compared to the previous studies. This is because our questionnaire informed the respondents about the global-scale damages. Although the gaps are probably underestimated in each subject (sometimes an order of a magnitude smaller), these gaps are still regarded to be within the reasonable range. We obtained reasonable and conservative values as MWFs for the G20 countries.

4 Further discussions

Since the weighting factors derived here represent the economic value of one unit of damage, the economic value of the environmental impact related to each safeguard subject can be derived by multiplying its relevant reference value and its MWF. Therefore, the world total economic value (WTEV) of the annual environmental damage caused by human activity can be obtained by Eq. (8):

$$WTEV_{Impact, \ annual} = \sum_s RV_s \ MWF_s \ (s = HH, SA, BD, PP)$$
(8)

where RV_s is the reference value of each safeguard subject (Itsubo et al. 2015). The results are presented in Table 8. The WTEV of annual impacts was estimated to be approximately 5.1 trillion USD, which is equal to 6.7% of world's total GDP in 2013. In addition, using the MWF^{SA}s, we arrive at a result of approximately 2.5 trillion USD, which is equal to 3.3% of the world's total GDP.

Compared with the results of the Stern Review (Stern 2007), which estimates the economic damage due to climate change (2.5 to 10 trillion USD), and the findings of TEEB (2009) (several trillion USD), which estimates the economic damage accruing from the loss of an ecosystem service, our result is reasonable although it appears to be an underestimate for the following reasons. First, the reference value of social assets (4.49E−11) does not contain of the impacts of global warming because of its undeveloped functional model and lack of data. We should include the loss of social assets (such as damages arising from agricultural, forestry, and fishery production, and energy consumption) and land loss due to floods (all of which are considered in assessment reports such as that of the IPCC) in future estimations. In addition, currently, the loss of human health due to toxic releases and the loss of primary production due to acidification are also excluded from our reference values. The reference value regarding the loss of biodiversity is also underestimated in our study because we exclude damages other than that caused to

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[21] Kuriyama et al. (2009) is one of the representative study providing VSL estimates in Japan, which range from 1.9 million USD to 4.4 million USD in the context of traffic accident.

[22] The original value is 85,000 ELU (Environmental Load Unit, which was equivalent to the Euro in 1999) converted into 2013 international dollars here. For weighting factor for human health impact in EPS, see Steen (1999).

[23] The original value is 41,000 Euro (year 2000) based on the results using the contingent valuation method (CVM) and its data from nine countries to estimate damage costs due to impacts on human health (total sample strength is 1463).

Table 8 Annual global damage cost

Reference values estimated by LCIA method			Monetary values of annual damage based on MWF	Impact categories
	Amount of annual damage	units	USD tax equivalent	
Human health	7.87E+07	DALY	1.8.E+12	GW/AP/PO/WU
Social assets	4.49E+11	US$	1.1.E+12	FF/MR
Biodiversity	1.02E+02	specy	1.1.E+12	GW/LU/FF/MR/BR
Primary production	1.78E+02	100 million tons	9.9.E+11	LU/FF/MR/BR
WTEV			5.1.E+12	
World total GDP			7.6.E+13	
% of world GDP			6.7%	
Monetary weighting factors (USD per unit)			Weighted MWF	
Human health	1 DALY per person		2.3.E+04	
Social assets	1 USD per person		2.5.E+00	
Biodiversity	1 species per world		1.1.E+10	
Primary production	100 million tons per world		5.6.E+09	

World total GDP is 76 trillion dollars (PPP, current international dollar) in 2013 (World Bank)

GW global warming, *AP* air pollution, *PO* photochemical ozone creation, *WU* water use, *LU* land use, *FF* fossil fuel consumption, *MR* mineral resource consumption, *BR* biotic resource consumption

vascular plants and the impact of soil erosion due to mining in surrounding areas.[24]

5 Conclusions

This study calculated the MWFs for the G20 countries by conducting a large-scale survey using a uniform questionnaire. Random sampling was implemented, and a total of 6400 responses were obtained. In all the areas surveyed, the results were statistically significant at the 1% level, with the exception of monetary attributes for Mexico. Using the population-weighted values of each G20 community provided the following estimates of the MWFs: 23,000 USD for human health (per year), 2.5 USD for social assets (per USD of resources), 11 billion USD for biodiversity (per species), and 5.6 billion USD for primary production (per 100 million tons). The differences between the results of the developed and emerging G20 countries are considerably large, with the values generally being smaller in the former in purchasing power parity (USD) terms. The significant variations in these estimated results indicate that caution should be exercised while transferring the MWFs of biodiversity and primary production (which are related to the ecosystem) internationally or even within developed countries. However, the MWFs of the subjects related to human society (human health and social

assets), which show minor variations among the G8 countries, may be transferred within developed countries.

Our results indicate that the WTEV of annual impacts is approximately 5.1 trillion USD, which is equal to 6.7% of the world's total GDP and comparable to the findings of the Stern Review (Stern, 2007) and TEEB (2009), which calculated global economic damage due to climate change and loss of ecosystem service, respectively. While the main goal of this study is not to examine absolute impacts, rather impacts relative to some defined unit, we obtained reasonable MWFs on a global scale compared with previous studies and provide useful evidence of the difference in MWFs between developed and emerging countries.

The reference values in this study reflect the damages that have occurred on a global scale, and the evaluators are people in various different regions (e.g., 19 countries from the G20). Therefore, the MWFs of our study refer to the willingness to pay for a marginal reduction in the global environmental impact for different geographical scales (e.g., G20, G8, G20 excluding the G8 states, and each country). From this aspect, country-specific MWFs could be different from other national weighting factors, reflecting the damages that have occurred closer to home. This is a topic for further research and could be of significant help in conducting a cost–benefit analysis using LCA. For an LCA practitioner, these MWFs can be chosen depending on the aims of the application. In general, the reliability of country-specific weighting factors is higher than those at the global scale. If LCA users wish to share the calculated results internationally (e.g., among the member countries of the G8), it would be useful to know the weighting

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[24] We evaluated an annual marginal damage cost for the status-quo scenario. Thus, our analysis could be conservative as it disregards some impacts.

factors of the group countries (e.g., the MWF of the G8). If users share the results domestically, the country-specific MWFs would be helpful; however, it must be noted that the values reflect damages incurred on a global scale.

One of the biggest advantages of direct weighting in the LIME method is that unlike other integrated models, the data-generating process can be fully controlled across different countries/regions if the questionnaire is well designed. This means that with the LIME methods, we can directly compare individual behaviors in different countries and investigate how country-specific attributes (such as living standards or regulations) affect their WTP for each safeguard subject. Establishing cross-country heterogeneity allows us to formally link local estimates with global ones. Additionally, cross-country studies help extrapolate future value developments from the current estimates, especially when country-specific attributes are expected to change over time.

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