What determines the values of environmental benefits? Evidence from a worldwide survey

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Article

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Posted Date: September 24th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-838391/v1

What determines the values of environmental benefits? Evidence from a worldwide survey

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Abstract

One of the key obstacles to building international cooperation for environmental problems is the fact that environmental benefits are valued differently in different countries. But where does the disparity come from? This study gives an answer to this question by analysing large-scale survey data collected across G20 countries. Combining lifecycle impact assessment and economic valuation techniques, we found that people's perceptions of environmental benefits are in fact diverse, but are highly correlated with a few social indicators such as life expectancy, the Gini index, and subjective well-being. Our findings suggest that improving these social indicators in otherwise ill-equipped countries will facilitate convergence of people's perceptions and will thereby establish a common ground for tackling global environmental issues.

Keywords: sustainable development, G20 countries, environmental goods, global damage, lifecycle impact assessment, economic valuation, life expectancy, domestic income inequality

The relationship between economic growth and environmental conservation has been a longstanding concern for environmental and resource economists and policymakers. In 2015, the global agenda shifted from the United Nations' Millennium Development Goals to its 17 Sustainable Development Goals (SDGs), which comprise comprehensive targets, such as poverty eradication and sustainable use of natural resources. Since the common global future vision is now sustainable development, understanding the trade-off and balance between economic activity and environmental conservation has become increasingly relevant for policymakers to achieve consensus among different countries with diverse values and conditions [1].

To achieve this future vision, researchers should physically assess the following impacts. For example: To what degree has air pollution and its probability of occurrence affected society? What types of effects do the loss of ecosystems in certain areas (through land use) have on various functions, such as purification capacity, provisioning of biological resources, and climate regulating functions supported by the distribution of surrounding species? However, answering these questions is insufficient for internalizing the environmental impact into the socioeconomic system automatically [2,3]. We must also identify the degree of urgency and importance perceived by the society regarding such environmental effects—social weighting. Bateman and Mace [4] discuss the importance of incorporating such (especially monetary) social weightings into decision-making practice and estimate the benefit-to-cost ratios for investments in natural assets in the UK.

However, we know that such social weighting is not universal because the achievement degree for each SDG target varies from country to country [5]. They likely differ depending on the current situation and the type of goods/services affected [6]. In this study, interdisciplinary approaches collaborating lifecycle impact assessment and economic valuations led to revealing the degree of public acceptance of mitigating the multiple environmental damages in society using the current physical damages assessed as a reference status. Furthermore, a large-scale simultaneous survey in 19 G20 countries using a uniform questionnaire led to compare social weightings directly among different regions, for different types of environmental goods and individuals, and explore determinants of people's preference.

The most significant contribution of this study is the tentative grouping of people's preferences into four categories depending on whether they place more importance on biodiversity or human health. This categorization is strongly correlated to national conditions such as life expectancy, domestic income inequality (i.e. Gini index), and urban population density. Moreover, the degree of monetary social weighting (i.e. marginal willingness-to-pay; WTP) is more relevant for individual conditions, such as the perceived quality of life. Our findings provide novel insights into how sustainable consensus should be built among diverse regions and governments, and how environmental effects should be internalized into the global supply chain management. Our framework provides directions to those engaged in business sectors involving environmental management systems, in public sectors facing trade-offs among environmental damage mitigation policies, and other diverse agents in understanding and acting on the heterogeneous values of people across the world.

Lifecycle impact and economic valuation

LCIA studies use 'weightings' to integrate various environmental impacts into a single index and internalizes externalities as environmental information [7,8]. Such weightings are representative of the society's preferences; therefore, LCIA practitioners can apply them to evaluate the positive/negative externalities of goods and services. Using the LIME method (the Life cycle Impact assessment Method based on Endpoint modelling [9]), we assessed four types of environmental damage (i.e. endpoints)—on human health (as disability-adjusted life year or DALY), social assets (in US dollars or USD), biodiversity (as the expected increase in number of extinct species or EINES), and primary production (as net primary production or NPP)—from eight impact categories (Figure 1). These impact categories include climate change, air pollution, photochemical oxidants, water use, land use, fossil fuel use, mineral resource, and forest resource use. Four endpoints are defined as the subjects contributing social welfare through different aspects facing trade-offs. For example, funding wild life conservation might contribute to social welfare through recreational and educational opportunities, but also means that limited budgets/efforts can no longer be used for social security and health care system, which lead to declining social welfare through other aspects. We assessed human health and social assets as qualitative and quantitative impacts on society, biodiversity and primary production as qualitative and quantitative impacts on the ecosystem, respectively. Damage to human health is assessed as loss of life expectancy due to diseases like diarrhoea, malnutrition, and malaria caused by each impact category. Similarly, damage to social assets, biodiversity, and primary production is assessed as a loss of economic production, species, and plant growth, respectively.

[Figure 1]

The current amount of environmental damage for each endpoint is calculated by multiplying the annual environmental loads by the damage factor for each country, impact category, and substance (see the Method section, page 14, for the equation). We obtained 79 million DALY (*Human health*), 450 billion USD of valuable resources (*Social assets*), 100 EINES (*Biodiversity*), and 18 billion tons of NPP (*Primary production*) as the current annual damage [10]. Accordingly, we directly estimated the marginal utility for mitigating each damage by using a choice experiment in the cross-sectional social survey and calculated social weightings.

Data and choice experiment

The 19 selected G20 countries account for more than 70% of the total global GDP and exert significant influence on the global supply chain. We excluded the European Union because of budget constraints and to ensure survey efficiency. To ensure sampling efficiency, we selected urban areas with the largest economic scale and high population density for each country and implemented random sampling. Eventually, we randomly obtained response data from 200–250 and 500–600 households from emerging and developed countries, respectively, and 6,183 valid micro responses were obtained.

We conducted a large-scale simultaneous survey at these sites between August 2013 and March 2014 using a uniform questionnaire. The questionnaire includes explanations for the four types of environmental damage to ensure respondents understand the questions (Figures S1a–d in the supplementary information). It also includes questions about the perceptions of these subjects and a choice experiment (posing eight hypothetical choice situations, as described below) to estimate their marginal utilities for mitigating these damages, and questions about their individual current status such as subjective well-being (SWB) (life satisfaction and happiness), self-rated health (SRH) condition, income level, household size, and age.

The choice experiment comprised 16 alternatives (as environmental conservation policies) in various combinations of attribute levels for the four endpoints: (1) loss of human health (DALY), (2) loss of biodiversity (EINES), (3) loss of valuable resources (USD), and (4) loss of plant growth (NPP), with environmental tax (i.e. the income decrease) as a numeraire. Respondents were asked to choose the desirable one from three policies: Policies 1 and 2 were adjusted for hypothetical situations like environmental improvements and additional tax payment. Policy 3 referred to the current situation with no additional tax as the status quo option. An example of a choice experiment is shown in Figure S2 in the supplementary information.

To develop social weighting factors to integrate various environmental effects that reflect the perceived degree of importance of each damage, we adopted two measures of social weighting: the dimensionless weighting factor (WF1) [11,12] and monetary weighting factor (WF2) [13–15]. WF1 was normalized to ensure that the sum of the four endpoints' WF1s is one, according to the general method of integration in the LCIA [9,12]. We calculated the relative importance, defined as the ratio of marginal utility, of each endpoint's annual damage to the total (sum of) marginal utilities of all subjects. By definition, a WF1 of more (less) than 0.25 indicates relatively larger (smaller) perceived importance in the country. WF2 represents benefits (i.e. external costs) comparable with conservation costs in a cost-benefit analysis. WF2 is defined as the marginal rate of substitution between each subject and income. Thus, WF2 demonstrates how much income people can give up to mitigate each damage. As the unit of income is purchasing power parity (PPP) USD, WF2s indicate the extent to which people can give up their living standards to mitigate the global damage to each endpoint (i.e. environmental good), regardless of their national income level.

The marginal utilities of the four endpoints were obtained through a micro-econometric analysis of the choice experiment data. Thereafter, we calculated the national average weighting factors for the 19 countries. The full lists of the estimates are reported in Itsubo et al. [10], Murakami et al. [16], and in the supplementary information. First, this study reviews the findings from the cross-national analysis focusing on relative weighting of human society and ecosystem. Second, applying a latent class approach by using all response data from 19 countries simultaneously, we demonstrate that the estimated values as utility functions can be classified into four types of segments. Moreover, we identify the characteristics of segment classes by focusing on their national as well as individual conditions.

Overview of national averages

Figure 2 shows the result of country-level analysis for WF1 and WF2. A significant diversity of values is observed among countries, even if they evaluated the same amount of global environmental damages. Figure 2a shows a scatter diagram with each country's average WF1 and gross national income (GNI) per capita, with regression lines summarizing the relationship. The red solid and dotted lines demonstrate that the WF1s of human society (human health and social assets, respectively) are trending downward. The blue solid and dotted lines demonstrate that the WF1s of the ecosystem (biodiversity and primary production, respectively) are trending upward. This indicates that people in lower-income countries focus more on health damage, while those in higher-income countries focus more on natural resource damage, on a national average.

Figure 2b shows a scatter plot of WF1s focusing on human health and biodiversity, both of which are qualitative endpoints. These revealed particularly large differences in each category (i.e. human society and ecosystem). People living in the countries located in the upper left area, place more weight on biodiversity than human health. By contrast, people living in the countries located in the lower right area, place more weight on human health than biodiversity. People located around the 45-degree line in the figure place equal weight on the factors. Figures 2a and b show that, when facing a trade-off between mitigating damages to society (e.g. economic activity) and the ecosystem (e.g. environmental conservation), the priority of public policymaking depends on the country.

Figures 2c and d show scatter diagrams of the relationships between the GNI and WF2 of each country for human society (human health) (left) and social assets (right) (Figure 2c), and ecosystem (biodiversity) (left) and primary production (right) (Figure 2d). As WF2s represent the amount of benefits, which are comparable to conservation costs in terms of PPP, it reveals the extent to which people can give up their living standards to mitigate global damage to each endpoint. WF2s hold greater heterogeneity among countries with lower levels of GNI per capita, possibly because of non-income factors, such as living conditions, resources and their distribution, and cultural values. However, the degree of heterogeneity decreases and converges with an increase in the national income level. This trend is observed for approximately 16,000 USD (PPP) of GNI per capita, which echoes the empirical boundary of the 'middle income trap' [17–21]. Much of the evidence suggests that a jump in sustainable growth to a high-income country status (i.e. beyond the boundary) cannot be achieved without structural transformation [22], such as enhancing infrastructure and human capital investments [23,24] and instituting a sufficient governance system for resource distribution [25–28]. Thus, the countries categorized as 'high-income' by the World Bank [18] had achieved such transformation, with sufficient infrastructure and living standard, contrasting with other countries which had less than a middle-income level; for example, the difference among national average weighting factors may reflect the situation that environmental goods, such as good health and clean air, are normal goods that are easily available without inequality in high-income countries, while these goods are still a luxury because of the basic needs' insufficiency or uneven distribution in other countries with less than middle income levels. These findings suggest that the benefits estimated in a high-income country (especially more than 40,000 USD (PPP)) may be transferable to other high-income countries with small errors in a cost-benefit analysis of each national project. By contrast, in lower-income countries, the decision-making may not reflect the actual preferences (i.e. the local trade-off perception) if using equivalent values estimated in other countries (even if they are estimated in a similar-income-level country) as the local benefit. Considering factors other than the national income level is thus critical to estimating the local benefit of a global public policy, particularly in lower-income countries (especially less than 16,000 USD (PPP)).

[Figure 2]

Four types in preference

To explore the determinants of heterogeneity, we analysed the same response data simultaneously by applying the latent class approach [29,30]. This method captures variations in preferences by modelling individual utility functions as a mixture of several distinct preference groups. The full estimation results of coefficients, standard errors, and statistical significance are provided in the supplementary information.

Figure 3a demonstrates the four distinct preferences estimated by using a latent class logit model with sufficient validity in terms of significant coefficients and Akaike's information criterion. The size of the markers reflects their individual share of the sample. As with Figure 2b, Figure 3a shows the relative importance between human health and biodiversity; Class A1 (A2) located in the upper left (lower right) area implies the placement of more (less) weight on biodiversity than human health. Classes A3 and A4, located around the 45-degree line, indicate equal weight on both, with equal importance on all environmental goods for Class A3 and larger weight on qualitative subjects (DALY, EINES) than quantitative subjects (SA, NPP) for Class A4. Figures 3b and c show the results for countries with less than middle- and high-incomes, respectively. For countries lower than the middle-income level, four distinctive classes of M1–M4 are observed, with M4 providing remarkably high weighting of qualitative subjects. For high-income countries, there are three distinctive classes of H1–H3, with H3, which places higher importance on biodiversity, accounting for 60% of the sample.

Factors predicting heterogeneity

An important feature of the latent class approach is that the membership parameters show which type of people tend to belong to each group, with such distinct preferences as shown in Table 1. People living in countries with longer (shorter) life expectancy, smaller (larger) income inequality, and lower (higher) urban population density tend to belong Class A1 (A2) with larger weight on biodiversity (human health). Although Class A4 has similar characteristics to A2, a large proportion of forest area is correlated to the tendency of belonging to this class, with equal weight on biodiversity and human health. People living in countries with lower (although higher than A2 and A4) life expectancy, smaller income inequality, lower urban population density, and smaller proportion of forest areas tend to belong to Class A3, with equal importance on all four environmental goods.

Regarding Figure 3b for the nine countries with less than middle-income levels, the share of the sample is similar between Class M2 with a larger weight on biodiversity, and M3 with larger weight on human health. People living in countries with a higher (lower) urban population density and shorter (longer) life expectancy tend to belong to M3 (M2). Class M4, which places a larger weight on qualitative subjects, is a segment to which people living in countries with a significantly higher Gini index (larger income inequality), such as Brazil and South Africa, tend to belong. Class M1 is similar in terms of equal weight on human health and biodiversity, but quite different from M4, as it does not focus on qualitative subjects alone. In addition, considering individual attributes, respondents with relatively higher income than their neighbours tended to belong to Class M2. Interpreting this result in conjunction with the fact that the national averages of these nine countries are located in the lower right area (as shown in Figure 2b), we found that some respondents with higher relative income within each survey site are more likely to place a higher weight on the ecosystem.

Figure 3c shows 60% of the respondents belonging to Class H3 with a higher weight on biodiversity, for the 10 high-income countries. Longer life expectancy and lower urban population density are positively correlated to the probability of belonging to Class H3. However, people living in countries with larger income inequalities, such as the US and Saudi Arabia, tend to place more weight on human health (Class H2) even though they are high-income countries. In addition, a certain group of people belong to Class H1, with equal weight on human health and biodiversity. Higher urban population density is positively correlated to the probability of belonging to this class.

[Figure 3]

Individual heterogeneity

An additional interesting finding associated with individual attributes is that the marginal utility of income change is remarkably large for the classes (A4, M4, H1) of people with lower SWB (measured by 'life satisfaction' as an individual perceived quality of life, described in the Method section), as shown in Tables S4–6 in the supplementary information. This larger marginal utility of income change leads to lower external costs (i.e. monetary social weighting described by WTP) for the class, which is consistent with previous literature [31,32]. Thus, people with lower SWB have larger marginal utility of income decreases, which means a greater aversion to monetary loss, leading to smaller external costs defined as the marginal rate of substitution between environmental goods and money. This trend is more pronounced for middle-income countries, wherein the magnitude of their WTP may be strongly linked to the individual subjective living conditions (Figure S3 in SI). Despite potential biases from the 'subjective' index measured by the self-report rating scales [33,34] and endogeneity concerns, SWB possesses useful information related to quality of life at an individual level, in contrast to GDP as a national index. While the existence of universal relationships between SWB and socio-demographic characteristics is uncertain, recent empirical studies [35–37] have shown a similar general structure globally across different levels of economic development and cultural values, at least for several important factors including income, employment, physical health, family status, and age. The correlation between such characteristics and SWB within our sample is generally consistent with prior evidence after controlling for the country dummy considering the national baseline (reflecting cultural values), as shown in Table S7 in supplementary information. These facts indicate that perceived quality of life can be an essential clue to predict heterogeneity in WTP (i.e. external costs). Thus, future research on the relationship between SWB and respondents' socio-economic attributes related to public policies can be useful to predict heterogeneous WTP for various national income levels and cultures.

Discussion

A significant contribution of this study is providing empirical and quantitative evidence that people have different priorities when making decisions on national projects to meet global goals. The cross-national analysis indicated that people in higher-income countries prefer to mitigate global damage to the ecosystem than damage to the human society, while the opposite is true for people in lower-income countries. Regarding monetary social weightings (WTP), the larger heterogeneity, which is observed among lower-income countries, decreases and converges when these levels increase beyond the boundary, which is consistent with the 'middle-income trap'.

Despite this comparative analysis by country indicating that it is not easy to build multilateral cooperation because of the diversified interests of different countries, the findings of the latent class approach provide a practical insight into international cooperation. This approach reveals four distinct groups with different trade-offs among the different environmental damages across the 19 countries. Similar social weightings imply that a common ground are ready to establish a cooperative relationship between groups. Note that life expectancy, domestic income inequality, and population density are significantly associated with such classification; for example, longer life expectancy is correlated to the higher weight on biodiversity. Larger domestic income inequality (Gini index) is correlated to the higher weight on human health. Hence, such national statistics are significant indicators for predicting the regional preference of environmental goods. Moreover, improving these social indicators in ill-equipped countries will facilitate convergence of people's perceptions and will thereby contribute to establish a common ground for tackling global environmental issues.

Regarding individual heterogeneity, the relative income level of households within a region is significantly positively correlated to the higher social weighting on biodiversity among the middle-income countries, where such gaps in interests according to income difference should be considered for policymaking. Our findings indicate that an improvement in the average health condition, reduction in income inequalities, and decrease in urban population density contribute to many people assigning a higher priority to the ecosystem. Simultaneously, this indicates that the current COVID-19 pandemic-induced declining average health conditions and growing income inequality may slow down the pace of international cooperation on environmental issues. Proper measures to mitigate health risks and income disparities [38] will also have a strong influence on the progress of environmental resource conservation projected by SDGs.

Method

Measures of environmental damages

We assessed the current level of global damages as the four endpoints presented below. The explanations provided in the questionnaire are presented in Figures S1a–d.

Human health (HH): DALY

The concept of DALY was developed by the World Bank and World Health Organization (WHO) to quantify the global health loss due to deaths and illnesses. It is widely used as a summary measure of the global burden of disease in the WHO's annual reports [39,40]. DALY is thus defined as the global loss of life expectancy, as follows:

$$DALY = YLL + YLD$$

$$= \int_{x=a}^{x=a+L} Cx \exp(-\beta x) \exp\{-r(x-a)\}\, dx + \int_{x=a}^{x=a+L_a} DCx \exp(-\beta x) \exp\{-r(x-a)\}\, dx.$$

DALY has two components: years of life lost (*YLL*), which measures the burden of premature death, and years lived with a disability (*YLD*), which measures the burden of living with a disease or disability in years. a is the onset age of disability or age of death. L is the difference between expected life in years and age of death, L_a is the duration of a disease or disability, and C and β are constant values of 0.1658 and 0.04, respectively. By definition, *YLL* and *YLD* both comprise time-integrated values for three types of weighting: (1) D (weight of disability), (2) $Cx \exp(-\beta x)$ (weight of age), and (3) $\exp\{-r(x-a)\}$ (time-discount). We only considered the weight of disability in our assessment of environmental damage (or loss of human health). However, in the social survey to estimate their marginal utilities, each respondent evaluated the global burden; hence, their evaluation should reflect their age and perceived time-discount [10,41,42].

Biodiversity (BD): EINES

As a measure of loss of biodiversity, EINES is defined as follows:

$$EINES = \sum_k \Delta R_k = \sum_k \left(\frac{1}{T_{a,k}} - \frac{1}{T_{b,k}}\right),$$

where ΔR_k denotes the change in the extinction risk of species k due to environmental burdens, such as climate change and land use. $T_{b,k}$ and $T_{a,k}$ are the expected time to extinction (life expectancy) of k before and after the environmental load occurs, according to the International Union for Conservation of Nature Red List. EINES is defined as the accumulation of expected changes in life expectancy of species k due to the environmental load. According to Lande [43], the factors influencing species' life expectancy ($T_{b,k}$ and $T_{a,k}$) include (1) the intrinsic rate of a natural increase (demographic stochasticity), (2) carrying capacity (environmental stochasticity), and (3) sensitivity to random catastrophes. Considering the various impact categories, including climate change and physical transformation of land due to events like resource extinction and deforestation in the LIME model, we assessed the amount of damage through land use by calculating the damage factors associated with a decrease in the plant population as carrying capacity. For damage due to climate change, we assessed the change in time to extinction caused by the change in the distribution of species k to adapt to temperature changes as sensitivity to random catastrophes [10,44].

Social assets (SA): USD

We assessed the damage to social assets from consumption of fossil fuels and mineral resources as quantitative damages to society, in addition to qualitative damage (human health). We adopted the user cost approach [45], which exhaustively evaluates non-biological resources. In this study, the amount of damage is expressed in USD applying a 5% discount rate [10]. User cost is broadly used as a measure of loss of income production capacity due to the depletion of natural resources (i.e. in green GDP). It is defined as the amount of savings required to ensure that the product sales incomes from resource extraction in the current and future generations are balanced, based on the idea of weak sustainability (c.f. replaceable assumption). While economic loss (i.e. decrease in income from agriculture, forestry, and fisheries) due to climate change can be considered in the LIME framework, these damages are excluded from the scope of this study at the time of our cross-national social survey because of insufficient environmental science knowledge; for example, large regional differences are expected between a region with revenue gain and one with revenue loss. Such distributions comprise important information to express the conditions of these regions, but it is generally lost during the process of aggregating the information to the global scale. This may lead to an underestimation of the amount of damage.

Primary production (PP): NPP

NPP is considered a measure of the quantitative impact on the essential foundation of energy flow in the ecosystem, in addition to the qualitative impact (i.e. biodiversity). NPP is defined as the production remaining after deducting cellular respiration from the gross primary production [47]. NPP acts partly as the origin of a biosphere cycle wherein herbivores consume plants as an energy source or assimilate and fixate inorganic carbon and other inorganic nutrients into organic matter by autotrophs. NPP is expressed in mass per unit area per unit time interval (i.e. production rate) and as typically dry matter production per unit area per year (e.g. t ha^{-1} yr^{-1}). Based on a simulation of the global vegetation distribution and temperature trend, we assessed the loss of plant growth per year (standardized with carbon) due to climate change or land transformation. The expected amount of loss varied from zero for deserts or the tundra to approximately 30 tons per ha per year for tropical rainforests [10].

The current level of damage for each endpoint

The current amount of environmental damage for each endpoint *s* is calculated by multiplying the annual environmental loads (*AEL*) by the damage factor (*DF*) for each country *c*, impact category *i*, and substance *x,* as follows [10]:

$$Annual\ damage_s = \sum_i \sum_c \sum_x [DF_s(i,c,x) \times AEL(i,c,x)], \quad s = HH, SA, BD, PP. \quad (*)$$

Social weightings

We adopted two measures of weighting: WF1 and WF2. The WF1 of each country *c* for subject *s* is derived from the following equation:

$$WF1_{s,c} = \frac{\beta_{s,c} \times Annual\ damage_s}{\sum_s (\beta_{s,c} \times Annual\ damage_s)}, \qquad s = HH, SA, BD, PP,$$

where $\beta_{s,c}$ is the marginal utility of each endpoint *s,* estimated using the choice experiment data of each country c. WF2 is derived from the following equation:

$$WF2_{s,c} = \frac{\beta_{s,c}}{\beta_{m,c}} \times F, \qquad s = HH, SA, BD, PP,$$

where F denotes the global number of households. WF2 is defined as the marginal rate of substitution between each subject and income.

Sample

We applied the most appropriate method for each survey site after consulting with a local research company. Table S1 in the supplementary information shows the national statistics, including GDP (economic scale), population, life expectancy, forest area, GNI per capita, Gini index, region category, and income group, as defined by the World Bank database. Table S2 shows survey information and regional statistics of the survey site. We adopted face-to-face interviews for emerging countries, wherein trained interviewers visited each household and explained the questionnaire to respondents in detail to minimize survey bias [48]. Internet surveys were used for developed countries with higher internet diffusion rates. The survey details are provided in previous publications [10,16].

Choice experiment

We designed a hypothetical choice situation based on the current environmental damage on a global scale toward the four endpoints to estimate the respondents' marginal utility for these damages as described above. The questionnaire was translated into local languages. The units of tax and social assets were converted into the local currency by using the PPP exchange rate. A more detailed explanation of the questionnaire is provided by Murakami et al. [16].

Random parameter logit model for national average preference

The choice experiment data were analysed statistically using a random parameter logit model by each country. We estimated the marginal utilities by applying the following function:

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

This describes the utility of respondent n obtained from choosing alternative i. x_{si} is an attribute vector for the loss of each endpoint s on *HH*, *BD*, *SA*, and *PP* with alternative i. m_i is a monetary attribute indicating an income decrease due to an additional tax. γ equals 1 if alternative i is the status quo (with Policy 3 as a current situation). ε_{ni} is a random term that includes all effects due to the unobservable information of alternative i and respondent n. Using the maximum simulated likelihood method, we estimated the marginal utilities of environmental damage, income decrease, and current status as β'_{ns}, β_m, and β_0, respectively. Following several economists [49–51], we interpreted the marginal rate of substitution among them as indicating their quantitative trade-off relationship since marginal utility is the degree of marginal importance of goods and services. Thus, $-\beta_s/\beta_m$ is the marginal WTP for mitigating each environmental damage; For example, respondent n is willing to pay $-\beta_{nHH}/\beta_m$ for mitigating human health (DALY). Similarly, β_{nHH}/β_{nBD} directly indicates the relative weight that respondent n perceives, so that each national average is interpreted as a national weighting factor of each endpoint, thereby indicating the social acceptance for a mitigation level.

Latent class approach for classification

Using the latent class logit model, we estimated the conditional utility function for each class, while assuming that the respondents included several distinct preference groups with different marginal utilities. Simultaneously, we estimated the probability of respondent *n* belonging to Class M. Thus, we used maximum likelihood procedures to estimate the coefficients for each class and then calculated the probability that an observation is located within each class, based on the observed choices of the respondents. We defined the probability of respondent *n* choosing y_n as follows:

$$P_n(\theta) = \sum_M \frac{exp\ \lambda_M z_n}{\sum_M exp\ \lambda_M z_n} K_n(y_n|\beta_M),$$

where θ is the vector of the parameters, λ is the vector of membership parameters, *z* is the vector of the observed characteristics of respondents, $K_n(y_n|\beta_M)$ is the conditional probability of respondent *n* belonging to Class M and choosing y_n, and β_M is the vector of marginal utilities.

The latent class approach allows us to explore the following: First, distinct utility functions (as a vector of marginal utilities) were estimated for each class, so that several classes with different vectors of marginal utilities are identified. Second, membership functions consisting of individual characteristics are estimated simultaneously, so we can explore regional and individual factors influencing heterogeneity. We applied the expectation-maximization (EM) algorithm to solve the difficulty of estimation due to many parameters being estimated [49,52].

Measures associated with SWB

SWB is defined as the appraisal and evaluation of one's own life to reflect cognitive judgements [53]. Many governments and international organizations incorporate SWB into official statistics to capture aspects of society's real conditions that are missed in the GDP and use it for policy decision-making [54–57]. Many empirical studies have supported the validity and comparability of SWB because of its association with blood flow to the brain, experience with immunological and hormonal measures, mortality, and short-term stability [58,59]. While there is a large variety of factors influencing SWB, from genetic to societal [60], the literature indicates that genetic factors influence 30–40% of SWB [61]. This means that the remaining 60–70% can be influenced by social situations associated with policymaking.

Life satisfaction

Respondents were asked to respond subjectively to the question 'All things considered, how satisfied are you with your life as a whole these days?' They answered by choosing a number from 0 to 10, with 10 being 'very satisfied', 5 being 'neither satisfied nor dissatisfied', and 0 being 'very dissatisfied'. OECD [57] recommends the use of life satisfaction, as well as the UK Health & Wellbeing Report and EU Statistics on Income and Living Conditions adopting it as a major social index.

Happiness

Respondents were asked to respond subjectively to the question 'Generally speaking, how happy are you with your life?' They answered by choosing a number from 0 to 10, with 10 being 'very happy', 5 being 'neither happy nor unhappy', and 0 being 'very unhappy'. Since happiness is a more emotional measure than life satisfaction, it is important to identify both these SWB measures. Specifically, 'happiness' may have a different definition in each country, depending on their cultural values and norms [62,63].

SRH

Respondents were asked to respond subjectively to the question 'How would you describe the current state of your health?' They answered by choosing a number from 0 to 10, with 10 being 'very healthy', 5 being 'neither healthy nor unhealthy', and 0 being 'very unhealthy'. SRH is closely related to perceived happiness and life satisfaction; For example, the influence of GDP per capita on SWB tends to reduce when considering additional explanatory variables, such as the health condition [60]. Thus, it is reasonable that an increase in wealth leads to a higher SWB, partially because of better health conditions.

Income class (relative income level per region)

Respondents were asked to specify their total monthly/annual household income based on 5 income ranges, 1 being the lowest and 5 being the highest with 3 as the local average income range in the survey site. Respondents could decline to answer. The well-known 'relative (comparison) income hypothesis' supports that individual SWB, such as happiness and life satisfaction, is associated with not only the absolute level of own income but also its relative level compared with those of others with similar socioeconomic attributes [64,65].

Age

SWB often has a U-shaped relationship with age; For example, the happiness point of middle age (40–50 years) is lower than for younger (20–30 years) and older (over 60 years) age groups. This relationship possibly depends on each region's socioeconomic systems. In this study, a U-shaped relationship was observed among higher-income countries, while there were no obvious trends among lower-income countries.

Limitations

For sampling efficiency, we selected an urban area with the largest economic scale and a high population density as the survey site for each country and implemented random sampling. This possibly resulted in higher monetary social weightings (i.e. WF2s defined as WTP) and higher SWB than the national average, reflecting less scarcity of wealth because of their higher income level. The income gap between urban and other areas tends to be larger for middle-income countries as shown in Figure S3 in SI. As our estimates are representative of these cities (survey sites), further investigation is needed to clarify whether this can be extrapolated to the national level. Nevertheless, this concern may be alleviated because the factors mainly associated with heterogeneity (shown in the table below Figure 3) are at a national level.

The LIME model used in this study provides the framework incorporating multiple impacts into social decision-making using an interdisciplinary LCIA approach. The public importance of mitigating the multiple environmental damages is evaluated using the current damages physically assessed as a reference status. Since potential damages cannot be fully captured in the assessment because of insufficient knowledge of environmental science, the estimated physical damages of the four endpoints (i.e. DALY, social assets, EINES, and NPP), posed to the respondents as the current damage levels, may be underestimated. This could result in smaller estimated marginal utilities of environmental goods. We can expand the same framework with up-to-date knowledge.

Despite the complications and difficulties of incorporating biodiversity mainly due to its multifunctional features, its appraisals need to incorporate socio-economical urgency/importance regarding its damages into public decision-making. Bateman and Mace [4] suggest a comprehensive framework of ecosystem service assessment. This study's social weighting of the ecosystem (i.e. biodiversity and primary production) is one example, wherein the weighting factor of biodiversity is defined as the WTP (or the relative size of marginal utilities) to avoid the extinction of one species. This does not consider differences that are associated with the organism involved. Increased spending is prevalent to avoid extinction of animals [66], suggesting that it may be desirable to estimate the social weighting per species for each organism. In this study, another social weighting of the ecosystem (i.e. primary production) is defined as a factor to capture the importance of the essential foundation of energy flow in the ecosystem. Further improvement and expansion of ecosystem service assessment is needed, which can promote interdisciplinary collaboration and help achieve progress in sustainable development.

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Acknowledgments

We are grateful to JSPS (Japan Society for the Promotion of Science). K.K. acknowledges support from the JSPS- RPD program. This large-scale simultaneous social survey has been supported financially by the Cabinet Office. We are grateful to the International Research Unit of Nikkei Research Inc. for its valuable support in conducting the social survey across various regions accompanied by local research companies.

Author Contributions

All authors contributed to the design and methodology of this study. K.M. led the survey design, statistical analysis, writing and revisions of the manuscript, with input from all other authors. K.K. provided the code for the latent class logit model with the EM algorithm. The initial concept for the LIME was developed by N.I. and K.K.

Competing Interests Statement

The authors declare no competing financial interests.

Data availability Statement

Supplementary information for this study is available online. Correspondence and requests for materials should be addressed to K.M.

Figure Legends

Figure 1. The framework of this study. This accords with the ISO14044 standard, wherein the lifecycle impact assessment (LCIA) procedure is specified. The inventory list and path are illustrative. For damage assessment, we covered eight impact categories including climate change, air pollution, photochemical oxidants, water use, land use, fossil fuel use, mineral resource, and forest resource use.

For each category, we quantitatively characterized the pathway from inventory emission to the four damage endpoints based on the latest knowledge in environmental science. In this study, we obtained 79 million DALY (human health), 450 billion US$ of valuable resources (social assets), 100 EINES (biodiversity), and 18 billion tons of NPP (primary production) as the current annual damage on a global scale based on 191 countries of occurrence [10]. Using these current damage levels, we estimated the marginal utility of mitigating each damage by using a choice experiment in the cross-sectional social survey of 19 G20 countries. This study compared national average social weightings calculated from marginal utilities estimated using each country's random parameter logit model (Figure 2) and tentatively classified all respondents from the 19 countries into four distinctive preference groups using the latent class logit model (Figure 3 and Table 1). DALYs=disability-adjusted life years; US$=US dollars; EINES=expected increase in number of extinct species. (See the Method section for detailed definitions of the four endpoints.) A complete overview of the LIME model is provided in Inaba and Itsubo [9].

Figure 2. Comparison among national averages of social weightings for 19 countries. (a) and (b) show that the social priority depends on countries: (a) shows a scatter diagram with each country's average WF1 (normalized social weighting) and gross national income (GNI) per capita, with a regression line summarizing the relationship. The red solid and dotted lines demonstrate that the WF1s of human society (human health and social assets, respectively) are trending downward. The blue solid and dotted lines demonstrate that the ecosystem WF1s (biodiversity and primary production, respectively) are trending upward. This indicates that the social weighting of the ecosystem (human society) is positively (negatively) related to the national income level on average. (b) focuses on the WF1s of qualitative subjects (i.e. human health and biodiversity). The upper left (lower right) area indicates larger weight on biodiversity (human health). The area around the 45-degree line indicates equal weight on both. BD=Biodiversity; HH=Human health. (c) shows scatter diagrams of the relationships between the GNI and WF2 (monetary social weighting in purchasing power parity; PPP) of each country for human society (human health (left) and social assets (right)). (d) shows those for the ecosystem (biodiversity (left) and primary production (right)). WF2s hold

greater heterogeneity among countries with lower levels of GNI per capita, and this trend decreases and converges after approximately 16,000 USD (PPP) of GNI per capita, which echoes the empirical boundary of the 'middle income trap' introduced by the World Bank and accepted by development economists. (See the main text for details.) DALYs=disability-adjusted life years; EINES=expected increase in number of extinct species.

Figure 3. Classification of each preference group focusing on human health and biodiversity. (a)–(c) demonstrate the several distinct preferences estimated using a latent class logit model for residents in 19 countries: 9 with middle income and 10 with high income. The marker size reflects their individual share within the sample. As in Figure 2b, Figure 3 demonstrates the relative importance of human health and biodiversity. (a) Class A1 (A2) located in the upper left (lower right) area implies the placement of more (less) weight on biodiversity than human health. Classes A3 and A4, located around the 45-degree line, indicate equal weight on both, with equal importance on all environmental goods for Class A3 and higher weight on qualitative subjects (DALY, EINES) than quantitative subjects (SA, NPP) for Class A4. (b) For countries lower than the middle-income level, four distinctive classes of M1–M4 are observed, with M4 providing remarkably high weighting of qualitative subjects. (c) For high-income countries, there are three distinctive classes of H1–H3, with H3 which places higher importance on biodiversity, accounting for 60% of the sample.

Table 1. Characteristics of each preference group. This table illustrates the group shares and the type of people that tend to belong to each group. + and - indicate significantly positive and negative observed correlations, while ++ and -- indicate stronger correlations. Shading indicates no significant correlations are observed between the classifications and the respondents' attributes. Overall, longer life expectancy is correlated to the probability of belonging to the class with higher weight on biodiversity (A1, M1, M2, M4, H3); shorter life expectancy and larger domestic income inequality (Gini index) are correlated to the probability of belonging to the class with higher weight on human health (A2, A4, M3, M4, H2). The household income class (relative income level within the region) is

significantly correlated to higher social weighting on biodiversity (M2) among the middle-income countries, despite having no significant impact on segmentation for the high-income countries.

Figures

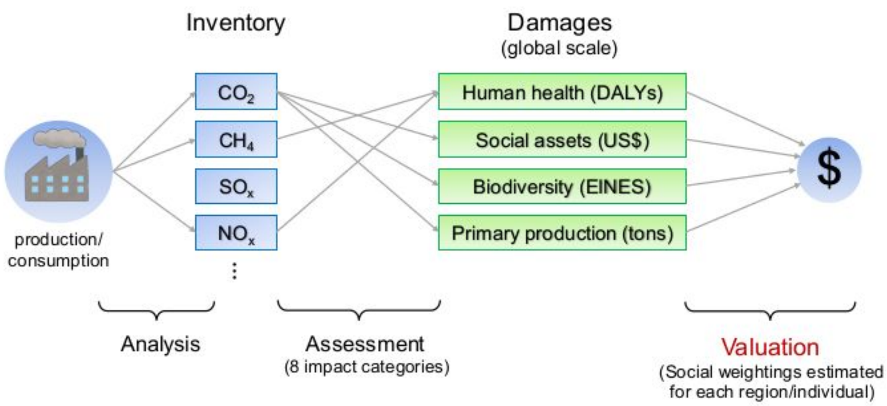

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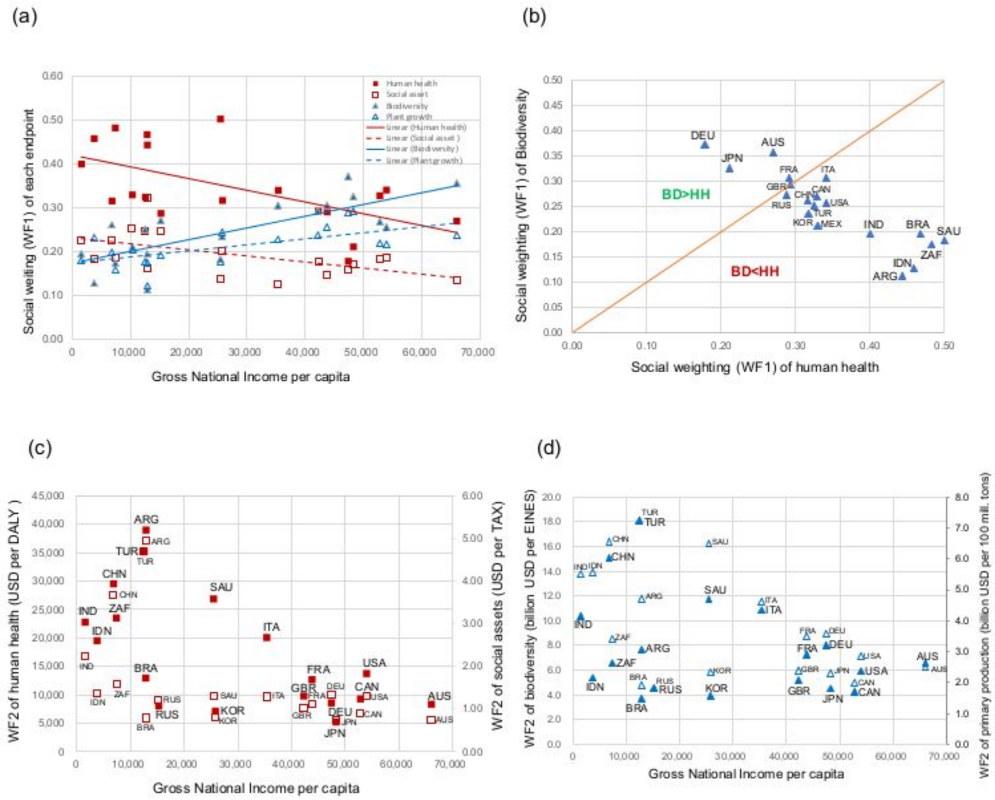
Figure 1

See image above for figure legend.



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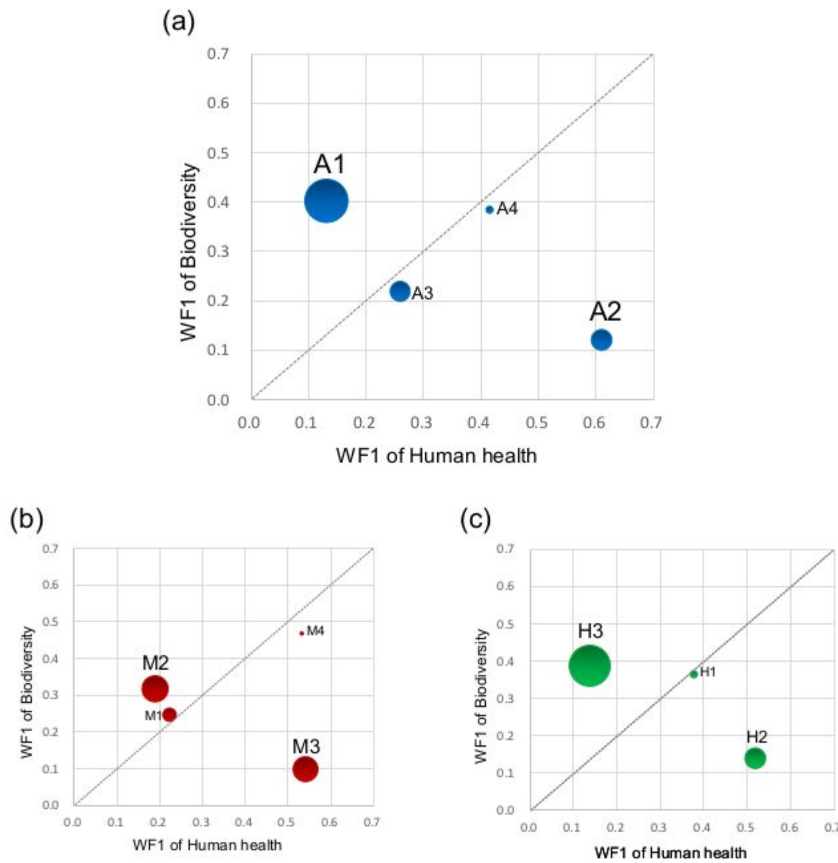

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Figure 3

See image above for figure legend.

Supplementary Files

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- Table1Characteristicsofeachpreferencegroup.pdf
- XSItablesfigures.pdf