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LETTER

Total economic costs of climate change at different discount rates for market and non-market values

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Supplementary material for this article is available online

Abstract

What will be the aggregated cost of climate change in achieving the Paris Agreement, including mitigation, adaptation, and residual impacts? Several studies estimated the aggregated cost but did not always consider the critical issues. Some do not address non-market values such as biodiversity and human health, and most do not address differentiating discount rates. In this study, we estimate the aggregated cost of climate change using an integrated assessment model linked with detailed-process-based climate impact models and different discount rates for market and non-market values. The analysis reveals that a climate policy with minimal aggregated cost is sensitive to socioeconomic scenarios and the way discount rates are applied. The results elucidate that a lower discount rate to non-market value—that is, a higher estimate of future value—makes the aggregated cost of achieving the Paris Agreement economically reasonable.

1. Introduction

The Paris Agreement states that all nations should promote mitigation, adaptation, and finance for developing countries to cope with the challenge of climate change. However, the world's pursuit of these goals is not on track (Rogelj *et al* 2016, Höhne *et al* 2020). One reason could be that mitigation measures bring economic costs similar to the adverse climate change impacts (Sanderson and O'Neil 2020). Numerous studies have attempted to quantify the mitigation costs and adverse impacts of climate change. Burke *et al* (2015) derive econometrics-based damage curves for each nation and claim that limiting the global temperature rise to 1.5 °C–2 °C has economic benefits. Using cost-benefit-type integrated assessment models (IAMs), some studies claim that the 2-degree goal is economically efficient (Glaneman *et al* 2020). In addition, another recent study has shown that the social cost of carbon (SCC) dioxide would be much higher if updated scientific knowledges are taken into account (Rennert *et al* 2022). However, others have shown contradictory results, depending on their methodologies and economic assumptions (Lomborg 2020). Detailed-process-based IAMs are more informative than cost-benefit-type IAMs, providing climate change impacts by sector and by region as well as mitigation cost. Although detailed-process-based IAMs have been widely used for climate change impact studies, these studies have focused on impacts of specific interests (Weyant 2017). Efforts to apply detailed-process-based IAMs more systematically to climate decision making are now underway.

Another important but often neglected issue is how to treat non-market impacts, such as the value of biodiversity and human life. To incorporate these impacts into a cost-benefit analysis, we need to monetize them. Moreover, one needs to set discount rates for the distant future. The choice of the discount rate and its influence on impact assessments have been debated (Interagency Working Group on Social Cost of Greenhouse Gases 2021). Benefits and costs are usually discounted at the same rate, but in the healthcare sector, the discount rate for non-market values can be lower than that for market values (Baumgärtner *et al* 2015, Baker *et al* 2019). Even applying a discount rate to non-market values is criticized as these values should not be weighted by time, that is, the present or future (Daly and Cobb 1989, Fearnside 2002). Thus, the debate on the way to apply the discount rate for non-market values is diverse and inconclusive (Attema *et al* 2018).

This study contributes to the literature on climate change impact by estimating both market and non-market impacts and illustrates the influence of applying differentiated discount rates. We assess the aggregated cost of climate change between 2010 and 2099 using a combination of a few shared socioeconomic pathways (SSPs) (Riahi *et al* 2017) and a few representative concentration pathways (RCPs) (Meinshausen *et al* 2011). We consider the mitigation costs and impacts of climate change on biodiversity and human health, as well as economic impacts, on account of eight risk factors. The impacts are estimated by a bottom-up approach; a detailed-process-based IAM (Fujimori *et al* 2012, Takakura *et al* 2019) and life cycle impact assessment (LCIA) (supplementary discussion 3). Instead of discussing what discount rate is appropriate, we consider two scenarios for discounting: one applies the same discount rate to both market and non-market values, and the other differentiates between the two. It shows that the aggregated cost of the stringent mitigation efforts would be reasonable with a lower discount rate for non-market values.

2. Method

2.1. Climate change scenarios and social-economic pathways

The study assesses climate impacts and mitigation costs for the period 2010–2099 for scenarios of SSP1 and RCP2.6/4.5/6.0, SSP2 and RCP2.6/RCP4.5/RCP6.0/RCP8.5, and SSP3 and RCP4.5/RCP6.0/RCP8.5. The climate forcing is a major factor in calculating climate impacts, and the fifth phase of the Coupled Model Intercomparison Project (CMIP5) data is used in this study. CMIP5 did not contain RCP1.9, therefore RCP1.9 was also not considered in this study. Even for CMIP6, the availability of GCM estimates for RCP1.9 is limited, and low-uncertainty estimate of climate change impacts for RCP1.9 is an issue for the future study. The baselines of SSP1 and SSP2 are lower than RCP6.0 and RCP8.5, respectively; however, they are approximated in this study.

2.2. Market impacts

2.2.1. Economic impacts

This study assesses climate change impacts on an economy on account of eight risk factors: agricultural productivity, undernourishment, cooling/heating demand, occupational health cost, hydroelectric power generation capacity, thermal power generation capacity, fluvial flooding, and coastal inundation. The details of the assessment framework used follow Takakura *et al* (2019). In the framework, these impacts are first calculated for a 0.5° × 0.5° grid and then aggregated to 17 regions as inputs to the Asia-Pacific integrated model/computable general equilibrium (AIM/CGE) model (Fujimori *et al* 2012), or directly monetized using econometric damage functions that translate physical impacts into monetized impacts. This study aggregates them and assesses the worldwide impacts. The impacts of human loss owing to undernourishment and fluvial flood are separated from the economic impacts and considered as health impacts in section 2.3.1.

2.2.2. Mitigation costs

We use the AIM model (Fujimori *et al* 2017) to calculate the change in gross domestic product (GDP) for each SSP/RCP scenario. A greenhouse gas (GHG) emission constraint and a GHG emission price path are assumed based on the SSP/RCP scenarios, and the model represents the implementation of mitigation actions. For each SSP scenario, there is a GDP scenario of 'business as usual'. The mitigation cost for each SSP/RCP scenario is estimated as the difference in GDP from that in the SSP's business-as-usual scenario. The climate forcing levels of the business-as-usual scenario for SSP1 and SSP2 is lower than RCP6.0 and RCP8.5, respectively, and the mitigation costs of SSP1-RCP6.0 and SSP2-RCP8.5 are assumed to be 0 in this study.

2.3. Non-market impacts

2.3.1. Health

Three causes of death are assessed as health impacts: undernourishment, fluvial flooding, and heat-related excess mortality. The mortalities are estimated following Takakura *et al* (2019).

These impacts are reassessed based on disability-adjusted life year (DALY) and a monetary factor taken from Murakami *et al* (2018). The health impacts are estimated as the difference in impacts between each RCP scenario and no climate change scenario

$$I_{i,j,k,l}\left(t\right)\left[\mathrm{US\$}\right] = D_{i,j,k,l}\left(t\right)\left[\mathrm{DALY}\right] \times P\left[\mathrm{US\$}/\mathrm{DALY}\right] \tag{1}$$

$$D_{i,j,k,l}\left(t\right)\left[\mathrm{DALY}\right] = N_{i,j,k,l}\left(t\right)\left[\mathrm{death}\right] \times C_k\left[\mathrm{DALY/death}\right], \tag{2}$$

where $I_{i,j,k,l}\left(t\right)$ is the monetized health impact for SSP i, RCP j, health sector k and GCM l in year t, $D_{i,j,k,l}(t)$ is DALY for each of SSP, RCP, health sector and GCM in year t. P is a monetary factor from DALY to US$ established in Murakami *et al* (2018) (US$ 23 000 per year). In equation (2), $N_{i,j,k,l}\left(t\right)$ is the number of deaths for SSP i, RCP j, health sector k, and GCM l in year t calculated in Takakura *et al* (2019). C_k is a conversion factor from the number of deaths to DALY for each of health sector k established in Tang *et al* (2019).

2.3.2. Biodiversity

Extinction of birds, reptiles, mammals, amphibians, and vascular plant is assessed as biodiversity impacts in this study. The number of species extinct due to temperature increase is estimated based on the relationship between extinction ratio and temperature increase (equations (3)–(6))

$$J_{j,l,m}\left[\mathrm{US\$}\right] = B_{j,l,m}\left[\mathrm{species}\right] \times Q\left[\mathrm{US\$}/\mathrm{species}\right] \tag{3}$$

$$B_{j,l,m}\left[\mathrm{species}\right] = N_m\left[\mathrm{species}\right] \cdot \mathrm{dGT}_{j,l}\left[{}^\circ\mathrm{C}\right] \cdot \frac{\mathrm{dPDF}_{l,m}\left[-\right]}{\mathrm{dGT}_l\left[{}^\circ\mathrm{C}\right]} \tag{4}$$

$$\frac{\mathrm{dPDF}_{l,m}\left[-\right]}{\mathrm{dGT}_l\left[{}^\circ\mathrm{C}\right]} = \frac{\mathrm{PDF}_{\mathrm{RCP8.5},l,m}\left[-\right] - \mathrm{PDF}_{\mathrm{RCP2.6},l,m}\left[-\right]}{\mathrm{GT}_{\mathrm{RCP8.5},l}\left[{}^\circ\mathrm{C}\right] - \mathrm{GT}_{\mathrm{RCP2.6},l}\left[{}^\circ\mathrm{C}\right]}. \tag{5}$$

In equation (3), $J_{j,l,m}$ is the monetized biodiversity impacts for RCP j, GCM l and for the taxon m, $B_{j,l,m}$ is number of extinct species for each of the RCP, GCM and taxon, Q is a monetary factor to convert the number of extinct species to US$ established in Murakami *et al* (2018) (11 billion US$ per species).

In equation (4), N_m is the total number of species for the five taxa, or 11 122, 10 450, 5674, 7728 and 281 052 for birds, reptiles, mammals, amphibians, and vascular plants, respectively (IUCN 2017); $\mathrm{dGT}_{j,l}$ is the global mean temperature (GT) increase from 2010 to 2099 for RCP j and GCM l; and, $\frac{\mathrm{dPDF}_{l,m}}{\mathrm{dGT}_l}$ is increase of potentially disappeared fraction (PDF) per 1° increase of global mean temperature for GCM l and taxon m (supplementary discussion 3). PDF has been widely used in LCIA as an indicator of impact on biodiversity and is defined as the potential extinction ratio. Note that biodiversity impact ($B_{j,l,m}$) is not assessed for the total of the 90 year period (2010–2099).

$\frac{\mathrm{dPDF}_{l,m}}{\mathrm{dGT}_l}$, in equation (5), is calculated by dividing the difference in PDF at RCP8.5 and RCP2.6 for 100 years (1970–2070) by the difference in GT at the two RCPs over the same period. PDF over 100 years is calculated as follows

$$\mathrm{PDF}_{l,m}\left[-\right] = \mathrm{ER}_{l,m}\left[\mathrm{year}^{-1}\right] \cdot p\left[\mathrm{years}\right], \tag{6}$$

where ER is the extinction ratio per year estimated using the projected climate-driven habitat change data (1970–2070) for five taxonomic groups containing 8000 species (Ohashi *et al* 2019), following Tang *et al*'s (2017) methodology. p is set to 100 years in the study to be consistent with the time period of the GT in equation (5). The estimated extinction ratios (PDF) are about 5%–10% over 100 years, which is close to the value proposed in Urban (2015) (i.e. 5%–15%). The detailed calculation methodology is available in the supplementary.

2.3.3. Monetization of non-market impacts

This study considers health impacts and biodiversity impacts as non-market impacts (2.3.1 and 2.3.2). Monetization factors are estimated by Murakami *et al* (2018), using a questionnaire survey on people's willingness to pay for four protection areas (human health, social assets, biodiversity, and primary production) and evaluating the monetary weighting factors. Though Murakami *et al* (2018) estimated the monetary weighting factors for each of the G20 countries, only the mean factors for G20 countries are used in this study.

2.4. Discounting

The study considers two scenarios for discounting future values. One scenario applies the Ramsey formula to the discount rates of both market (economic impacts and mitigation costs) and non-market values (health and biodiversity impacts). In the other scenario, only market values are discounted using the Ramsey formula, but non-market values are discounted by a 0.1% constant rate. The 0.1% discount rate on non-market values is chosen taking into account the argument discussed in the introduction. The Ramsey formula is given in equation (7)

$$\rho(t) = \delta + g(t) \cdot \eta \tag{7}$$

where $\rho(t)$ is the discount rate for year *t*, δ is the sum of the utility rate of discount (how much people discount future generations), $g(t)$ is the growth rate of consumption (people gain more utility from consumption today than in the future because they expect to have a higher consumption level as a result of economic growth) assumed equal to the growth rate of GDP per capita in year *t*, and η is the elasticity of marginal utility of consumption that represents the elasticity of intertemporal substitution and risk/inequality aversion. The Ramsey formula well represents pure time preference, catastrophic risk, and consumption growth, that are main reasons why discount rates are used in future economic evaluations (Attema *et al* 2018).

The growth rate of consumption ($g(t)$ in equation (7)) is assumed to be equal to the growth rate of GDP per capita, which is the basis of a consumption level in the AIM/CGE model, it is calculated based on a projection of global GDP for non-market values, while it is calculated based on projections of regional GDP for market values.

Determining the other parameters δ and η is challenging (Arrow *et al* 2014). One approach to determine the parameters is to choose δ and η so that $\rho(t)$ would match a value such as market interest rate in the near future (e.g. Nordhaus 2014). This study assumes δ to be 0.5, which is lower than $\delta = 1.5$ in DICE model (Nordhaus 2007), but not as low as $\delta = 0.1$ in Stern (2007). η is set to 1.0 following the UK discount schedule (H M Treasury, Annex 6 2003). The estimated discount rates are around 2%–5% in 2010 for most of the regions and declines to around 2%–4% for SSP1 and SSP2 and 0.5%–2% for SSP3 in 2099.

3. Results and discussion

3.1. Aggregated climate change impacts and a comparison with previous studies

Similar to other studies, our results show that the impacts are highly dependent on the level of future greenhouse emissions and socioeconomic developments (figures 1(a)–(c)). The economic impact of undernourishment is estimated as negative values in some scenarios which translates into the economic benefit from climate change. Since the agricultural productivity in some regions has been reported to increase to some level of temperature rise, the impact of undernourishment could be reduced. That also explains why the health impact of undernourishment is lower in RCP6.0 than RCP4.5. Biodiversity impact shows a large uncertainty because of high sensitivity of estimation of extinction risk on rainfall pattern. Figure 2(a) shows the aggregated cost with Ramsey discount rate on both market and non-market values, and figure 2(b) shows Ramsey discount rate on market values and 0.1% time-constant discount rate on non-market values.

In both figures 2(a) and (b), if compared for the same RCP, mean aggregated cost could be smallest in SSP1. If compared for the same SSP, mean aggregated cost are smallest for RCP4.5 in SSP1 and smallest for RCP6.0 in SSP2 and SSP3 due to high mitigation costs, and stringent mitigation pathways would not be cost-effective, however, they are within the range of uncertainty, and more comprehensive and precise estimates of impacts would be needed to conclude. This tendency is not different after modifying the parameters of Ramsey formula due to the time series patterns of the impact sectors; mitigation costs come in the nearer future and so they are less discounted than economic impacts and non-market impacts. That said, when we include non-market values and apply different discount rates between market and non-market values, the 2-degree goal (RCP2.6) would not be too costly as depicted in figure 2(a) but reasonable, in particular for SSP1 (sustainable society scenario) as in figure 2(b).

The values in figures 1 and 2 are shown in supplementary tables 1 and 2. Supplementary figure 1 shows values of figure 1 in % of GDP, and supplementary figure 2 shows values of figure 2 in trillion US$. The conclusion from the supplementary figure 2 is same with that from figure 2(b). Note however that annual impacts could be larger than aggregated cost described above, as shown in table 1, for instance, that annual impacts except for the biodiversity impact for 2099 is as high as 8.67% of GDP for SSP3–RCP4.5.

Notably, the share of non-market impacts is larger than that estimated in previous studies. Our study includes only the impacts on the five taxa (birds, reptiles, mammals, amphibians, and vascular plants) and does not include the full taxon range such as fish and insects. In addition, we do not consider the health risks of vector-borne diseases, such as dengue fever or malaria, that have increased and are likely to worsen with increasing temperature (Rocklöv and Dubrow 2020). As our study does not include the full range of non-market impacts, our results likely underestimate them. It can be assumed that a more comprehensive

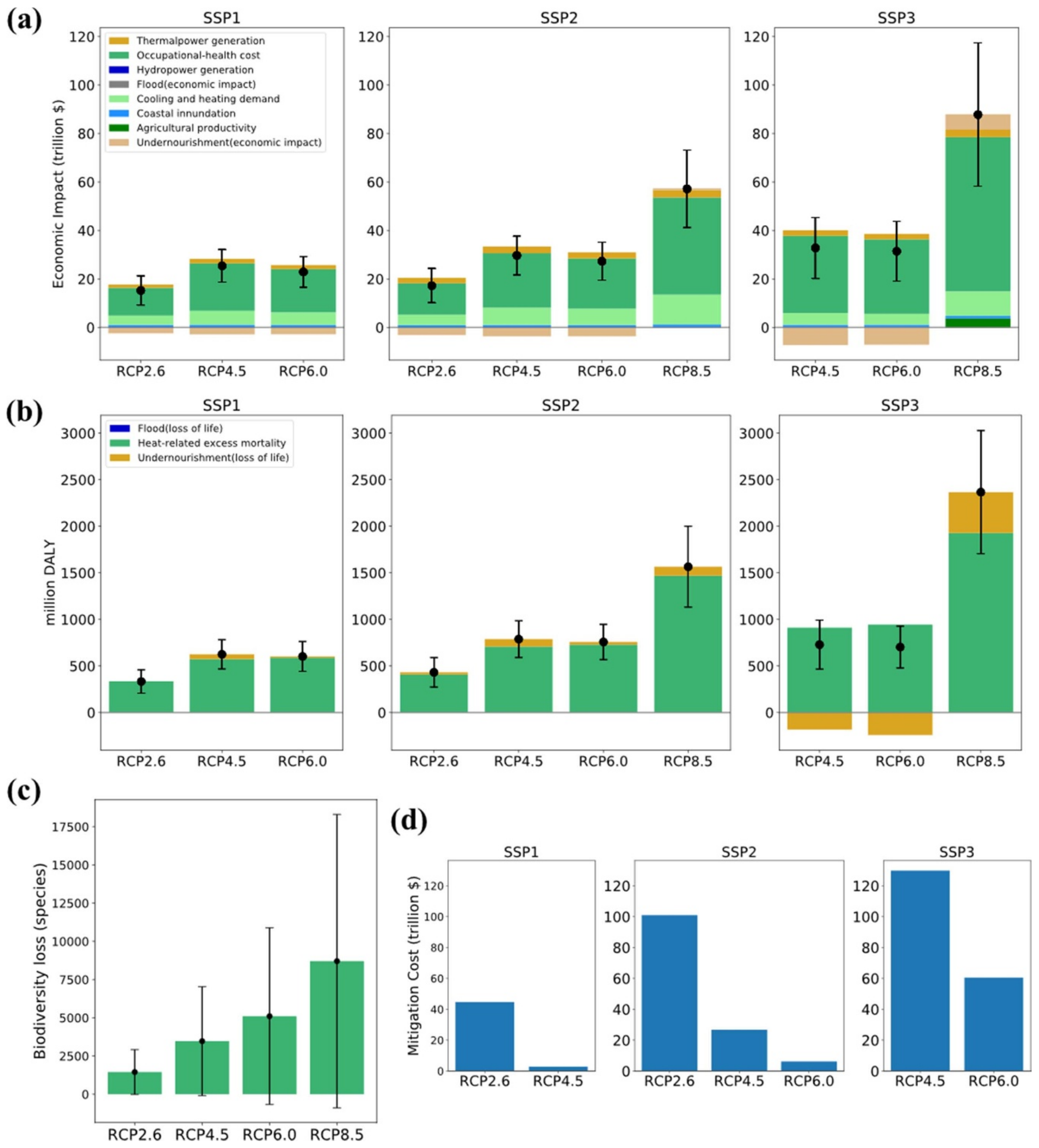

Figure 1. Climate change impacts on (a) economy on account of eight risk factors (agricultural productivity, coastal inundation, cooling and heating demand, flood, hydropower generation, occupational health cost, thermal power generation, and undernourishment), (b) health sectors (flood, heat-related excess mortality, and undernourishment), (c) biodiversity, and (d) mitigation costs. The values in (a) and (d) are shown as cumulated discounted values. The impacts are shown in a bar plot for all the SSP1–3/RCP2.6–8.5 combinations, excluding SSP1/RCP8.5 and SSP3/RCP2.6. The dots are the mean values, and the bars indicate uncertainties of 1-standard deviation of the results among the five GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M). The uncertainties are considered for all the sectors other than mitigation cost. Note: RCP: representative concentration pathway; SSP: shared socioeconomic pathway; DALYs: disability-adjusted life years; GCM: general circulation model.

consideration of non-market values would make the stringent mitigation pathway preferable.

The difference between the results of this study and those of Burke *et al* (2015) should be attributed to the different model structures and assumptions used. Our study is based on the detailed-process based models (bottom-up approach) and Burke's is study is based on a statistical regression model (top-down approach). In addition to this difference in the model structures, the former assumes temperature have effects mainly on the level of economic activity when the climate shock is given (level model) while the latter assumes the temperature affects the economic growth rate and the impacts accumulates in a multiplicative way (growth model). In general, impacts of climate change estimated by bottom-up models could be smaller than those by top-down models (for example, Figure Cross-Working Group Box ECONOMIC 1 in the IPCC AR6 WG2 (IPCC 2022)). Economic impacts estimated by the AIM/CGE model (Takakura *et al* 2019) used in this study would locate in the middle

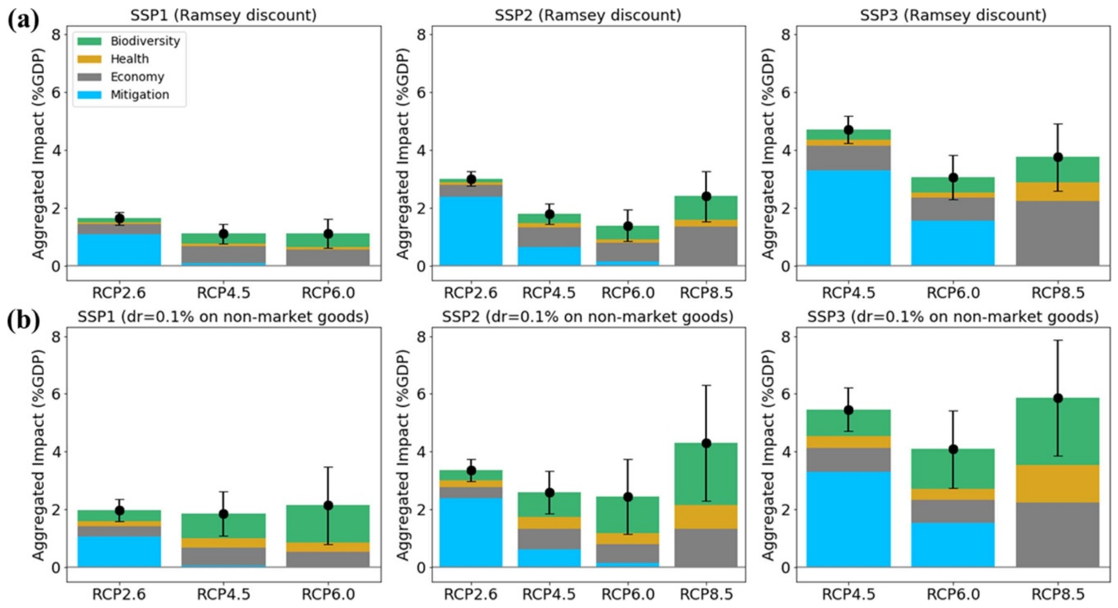

Figure 2. (a) Aggregated climate change cost with the Ramsey discount rate (dr) on both market and non-market values and (b) Ramsey discount rate on market values and time-constant discount rate of 0.1% on non-market values. The values are presented as % of GDP (i.e. cumulative discounted cost divided by cumulative discounted GDP). The dots are the mean values, and the bars indicate uncertainties of 1-standard deviation of the results among the five GCMs.

Table 1. Annual impacts except for the biodiversity impact in year 2050 and 2099. The values are presented as % of GDP and they means of five GCMs. Note, the biodiversity impact is not shown due to the difficulty of estimating its annual impact by our methodology: the methodology of life cycle impact assessment (LCIA) study usually considers incremental costs in a long time period.

			SSP1			SSP2				SSP3		
Year	Sector	Unit	RCP2.6	RCP4.5	RCP6.0	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP4.5	RCP6.0	RCP8.5
2050	Mitigation	%GDP	1.29	0.04	0.00	2.86	0.53	0.20	0.00	2.28	1.23	0.00
	Economy		0.36	0.68	0.51	0.35	0.66	0.50	1.09	0.61	0.44	1.16
	Health		0.03	0.05	0.04	0.05	0.08	0.06	0.12	0.10	0.05	0.21
	Total		1.69	0.77	0.55	3.26	1.28	0.76	1.21	2.99	1.72	1.37
2099	Mitigation	%GDP	1.25	0.32	0.00	2.47	1.04	0.11	0.00	7.30	3.27	0.00
	Economy		0.62	1.57	1.76	0.51	1.45	1.67	4.12	1.25	1.74	6.46
	Health		0.02	0.05	0.07	0.02	0.07	0.09	0.21	0.13	0.20	0.69
	Total		1.88	1.94	1.82	3.01	2.55	1.86	4.33	8.67	5.22	7.15

among other IAM models (for example, Warren *et al* 2021, IPCC 2022). While discussions continue about which assumptions would be appropriate (supplementary discussion 6), the study provides new insights for utilizing detailed-process-based IAMs for cost-benefit analysis of climate policies and further advances the discussions. Furthermore, our results show that considerations of climate change impacts on non-market values have a significant influence on cost-benefit analysis, and the mitigation pathways with minimum aggregated cost of climate change depends on socioeconomic pathways and differentiated discount rates for market and non-market values. These findings are novel and less sensitive to which method is applied for the assessment of market values. It is worthwhile to test the robustness of the findings against the use of other IAMs and against the cases in which more sectoral coverage is considered.

3.2. Uncertainties

Some uncertainties should be considered when interpreting the results here. First of all, the variation in market impacts among major IAMs represent a large uncertainty in the assessment. This uncertainty could be due to different values of parameters of damage functions each IAM relies on, difference in coverage of impact sectors and different assumptions of macroeconomic modelling in each IAM. Other damage functions such as that in Burke *et al* (2015) show larger market impacts. Van Der Wijst *et al* (2021) has developed a meta-model to disentangle the uncertainty of climate impact assessment and shown that the damage function would be the most important factor of the uncertainty.

Uncertainty in assessment of non-market impacts is huge as well. As is shown in figure 1(c), the biodiversity loss estimated using five GCMs differs a lot due to its sensitiveness to climate factors.

Supplementary figure 3 shows the difference in health impacts when assessed by a monetizing factor based on DALY by Murakami *et al* (2018) and when assessed by a value of statistical life (VSL) according to the Organisation for Economic Co-operation and Development guidelines (OECD 2012). Health impacts become larger when evaluated as a VSL, and the aggregated cost become larger when the atmospheric GHG concentrations are high (RCP8.5). There is also uncertainty regarding monetary factors in quantifying non-market values (supplementary table 3). In addition to the biodiversity value (assessed in this study), the social impacts of biodiversity loss can also be significant (Bastien-Olvera and Moore 2021).

Furthermore, there is great uncertainty regarding the mitigation costs (Van Vuuren *et al* 2020). Supplementary figure 4 shows mitigation costs estimated from different IAMs. The mitigation cost used in this study estimated by AIM (Fujimori *et al* 2017) is located in a lower to middle part in the spreads between IAMs for SSP1 and SSP2 and in a relatively higher part for SSP3. Last, the uncertainty regarding the mitigation cost of stringent mitigation pathway is substantial. Some studies have argued that using a no-policy scenario, as current IAMs do, as a reference to estimating mitigation costs could inflate them (Köberle *et al* 2021) because existing policies are already significant.

The uncertainty of parameters in Ramsey formula has already been mentioned in the method section. Rather than working on sensitivity analysis on those parameters, the study has focused on whether or not to differentiate discount rates between market and non-market values. That point has been discussed in the literature for a long time, however, it has not discussed in the assessment of climate change impact using bottom-up IAMs so far.

3.3. Future research scope

Although this study shows worldwide aggregated cost, the impacts and mitigation costs are not evenly distributed across regions, countries, or stakeholders (Tschakert *et al* 2013). Therefore, minimizing the aggregated cost of climate change is not necessarily ideal: rather, information disaggregated in regions and sectors may be serious for some decision makers (Warren *et al* 2021).

Furthermore, we did not examine the impacts, such as the risks of large-scale singularities, sometimes called tipping elements (Lenton *et al* 2008). For example, the disintegration of the Greenland and West Antarctic ice sheets leading to rapid sea-level rise, and major ecosystem regime shifts such as the degradation of coral reefs and Arctic systems, are out of the scope of this study. Although it is difficult to incorporate all the risks missing, interdisciplinary collaboration with both quantitative and qualitative approach would play a crucial role in impact assessment. (Rising *et al* 2022) The RCPs with minimum cost would be different accounting for the risks of such events. The result would help to promote life cycle assessment (LCA) and LCIA research. Finally, there are various ways for aggregating climate change impacts spatially and temporally, and choice of the aggregation method can affect how the evaluated results are perceived by a decisionmaker. While we highlighted the aggregated cost of climate change with Ramsey discount rate for aggregation in this study, we may also extend the study by adopting other aggregation methods, for example, the SCC, that could inform optimal carbon price.

4. Conclusion

The study demonstrates the integration of wide range of recent climate impact studies that are based on detailed-process-based models. The results show that mean aggregated cost would be smallest under sustainable society scenario (SSP1) for each RCP, the most stringent mitigation policy does not necessarily minimize the aggregated cost of climate change for each SSP because of high mitigation cost, and the minimum aggregated cost depends on which socioeconomic pathways we aim to develop and what discount rate we consider for future climate change impacts. Although uncertainties of impact assessments are large, the result indicates the importance of including non-market values such as human health and biodiversity to follow a decision to pursue stringent mitigation pathways. By including non-market values with market values in the cost-benefit assessment, this study elucidates that a lower discount rate to non-market value—that is, a higher estimate of future value—makes the aggregated cost of achieving the 2-degree reduction goal economically reasonable.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.15083/0002003740.

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Author contributions

T Oki, T Oda, J T, L T and N I developed the overall research framework, Y Hirabayashi, Y Honda, J T M Tamura., M Tanoue., T I, N K, Q Z, N H, C P, and H Y conducted analyses on the sectoral impacts and provided the data. S F, T H, K Takahashi, and Y Hijioka conducted the analysis of climate-change mitigation. J T and T Oda conducted the analysis of aggregated impacts. T Oda wrote the first manuscript, and all authors participated in the interpretation of the results, discussion, and revising the draft.

Conflict of interest

J T was employed by Toshiba Corporation, which is associated with the manufacture, sale, distribution, and marketing of hydro/thermal power plants, until February 2016. T Oda has been employed by Nippon Koei, which is associated with consultation on natural disaster prevention (including fluvial flooding and coastal inundation) and on hydro/thermal power plants, since April 2020. The other authors declare no competing interests.

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