Oxford Open Climate Change, 2022, 2(1): kgac003

https://doi.org/10.1093/oxfclm/kgac003
Research Article

RESEARCH ARTICLE

Net economic benefits of well-below 2°C scenarios and associated uncertainties

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ABSTRACT

Climate stabilization pathways reviewed by the Intergovernmental Panel on Climate Change depict the transformation challenges and opportunities of a low carbon world. The scenarios provide information about the transition, including its economic repercussions. However, these calculations do not account for the economic benefits of lowering global temperature; thus, only gross policy costs are reported and discussed. Here, we show how to combine low carbon pathways' mitigation costs with the growing but complex literature quantifying the economic damages of climate change. We apply the framework to the scenarios reviewed in the Special Report on 1.5°C of the Intergovernmental Panel on Climate Change. Under a probabilistic damage function and climate uncertainty, we show that Paris-compliant trajectories have net present economic benefits but are not statistically different from zero. After mid-century, most scenarios have higher benefits than costs; these net benefits are most prominent in developing countries. We explore the robustness of results to an extensive set of damage functions published in the literature, and for most of the specifications examined, we cannot reject the null hypothesis of net benefits. Future research could improve these results with a better understanding of damage functions with greater coverage of damages and including adaptation and its cost.

Key words: climate change; IPCC SR1.5C scenarios; mitigation costs; avoided impacts.

INTRODUCTION

Stabilizing climate change can be justified based on multiple grounds, most notably preserving planetary health. Economic motives for reducing emissions and adapting to a changing climate remain crucial, as they play an essential role in implementing mitigation policies and international negotiations. Reports such as those periodically produced by the Intergovernmental Panel on Climate Change (IPCC) have examined the macroeconomic and technological consequences of stabilizing climate at different levels. They have partly relied on low carbon pathways produced by numerical models integrating climate, economy, the energy and land-use sectors. These tools, or 'detailed process integrated assessment models' (IAMs) vary in nature, formulation and details, and are distinct from simple benefit–cost frameworks [1]. Their analyses have highlighted the economic consequences of implementing policy goals, such as those consistent with the Paris Agreement.

Submitted: 8 October 2021. **Received (in revised form):** 9 March 2022. **Accepted:** 15 March 2022

The mitigation costs of meeting the Paris goal are uncertain [2–5] and driven by policy, social and technology factors. They are often non-negligible in stringent scenarios. However, these economic assessments have mostly looked at only one side of the equation: that of policy costs. They do not include the economic benefits of reducing global warming, neither reported nor compared. This generates a partial picture of the economic appraisal of climate policy, which is focused on the gross costs of stabilization. Yet, decision-makers and society as a whole demand to know the net consequences of well below 2°C strategies.

Parallel literature, informed by a separate and disconnected family of IAMs, has focused on benefit–cost appraisals [6]. The major contribution of this literature has been to identify welfare-maximizing policies which dynamically equate marginal benefits and costs [7]. Scholars have discussed the limitations of a fully fledged benefit–cost evaluation [8]. Let alone the ethical considerations behind the idea of defining the optimal level of mitigation on the sole basis of cost–benefit considerations, integrating economic benefits have come at the expense of highly simplified modelling frameworks, none of which is present in the scenario database of the past IPCC reports (i.e. the fifth assessment report and the special report on 1.5°C). Damage functions are scarce, they were not built under the empirical rigour of current standards, they lack the temporal aspects impacting the abatement cost uncertainty and they entail many uncertainties. Because of these issues, and not to mention the normative elements embedded in fully integrated frameworks, detailed process IAMs have avoided featuring climate economic benefits. While this has simplified the discussion and reduced the uncertainties, it also separated the assessment of mitigation costs from the benefits deriving from avoided damages.

In recent years, the literature quantifying the economic impacts of global warming has significantly increased in scope and methods of assessment. The most significant contributions have been empirical approaches examining the historical relations between temperature variations and various outcomes, including economic ones. This new empirical evidence employs panel data approaches controlling for unobserved time-invariant group heterogeneity, such as differences in institutions between countries. The evidence points to a statistically significant and typically negative relation between temperature, economic growth and inequality [9–12]. The advantages of this new literature include reproducibility and quantification of uncertainties, which were significant sources of concern plaguing the previous generation of impact functions. Both are critical elements, given the many unknowns characterizing climate change impacts. Model uncertainty remains a significant concern for the empirically estimated impact functions: methodological questions remain about the extent to which the estimates can be interpreted as short-term, weather-related shocks rather than variability in long-term climate [13]. Estimates vary depending on whether climate influences the level versus the growth of economic activity and the model formulation assumptions [14]. The retrospective nature of the assessment also makes it impossible to include yet-to-come and/or unobservable physical and economic impacts, such as sea-level rise, non-market impacts of health and ecosystem services, or crossing specific tipping points, or simply crossing temperature ranges never observed before, something which is expected to happen at increased frequency [15].

Recently, some studies have introduced this new empirical knowledge into the simple benefit–cost IAMs. They have shown that Paris-compliant scenarios can be economically optimal [16–18] and that climate-induced economic inequalities will persist [19], unlike other studies that found or argued that greater than 2°C warming could be optimal [20]. Still, detailed process IAMs do not yet consistently account for the impacts from climate change along with mitigation cost assessment.

Here, unlike in optimal CBA, we are using existing well-below 2°C scenarios, reviewed in the IPCC and we assess the implied net economic consequences. This study aims to lie out an approach for integrating the vast amount of information emerging from the literature on potential economic damages in a way that is internally consistent with the decarbonization scenarios, without the need to resort to fully integrated, simplistic and partial frameworks. The unified framework we propose enables the comparison of mitigation cost and damage function estimates based on the same baseline for multiple decarbonization scenarios.

MATERIALS AND METHODS

The methodology is summarized in Fig. 1. We used the scenarios from the IPCC SR1.5C scenario database [21], in particular, the global mean temperature and the mitigation cost estimates until 2100. In the database, the temperatures have been generated by a probabilistic version of the climate model MAGICC, calibrated to replicate the climate sensitivity assessment from the IPCC report on the 1.5° [22]. The analysis employs the three available quantiles: the median, the 5th and 95th percentiles.

Policy scenarios, compliant with the Paris Agreement goal, are clustered according to their median temperature estimate in 2100: the '2°C' cluster contains the scenarios with temperature from 1.5°C to 2°C and the '1.5°C' cluster the scenarios with a temperature below 1.5°C. Some scenarios see a temperature overshoot, exceeding the temperature in 2100, in particular the scenarios of the 1.5°C cluster (see Supplementary Fig. S3). We associate each policy scenario with its baseline scenario, where no policy occurs, and with the shared socio-economic pathways SSP baseline scenario, which was used to calibrate the detailed process IAMs baseline. In our analysis, the baseline scenarios provide the global mean temperature increase and the SSP baseline scenarios provide the GDP per capita trajectories at the country level.

For the level-based damage functions [12, 20, 24, 25], we apply the quadric functions to the global mean temperature increase from preindustrial levels gmt. The global GDP loss is $\Delta \mathrm{gdp}_{cc} = \mathrm{gdp} \times (\alpha \mathrm{gmt}_t + \beta \mathrm{gmt}_t^2)$. gdp is the global GDP from the scenario (in baseline or policy). gdp_{cc} is the global GDP with the warming effect. The coefficients α and β are reported in Supplementary Table S1.

The growth-based damage functions [9, 10, 12, 26–30] are applied at country level. First, the global mean temperature is downscaled into population-weighted country-level temperatures according to 20 individual CMIP5 model patterns (see details in Supplementary Methods). The computation of the national GDP per capita with the warming effect follows the procedure described in Ref. [9] and as implemented in Refs. [27, 31]. GDP per capita is $g_t = g_{t-1}(1 + \eta_t + \delta(T_t))$, where η_t is the national growth rate in the SSP baseline scenario and $\delta(T_t)$ is the warming effect on growth, adjusted to the baseline year in 2010. The warming effect function coefficients are provided in Supplementary Table S2. We obtain the country-level gdp_{cc}, multiplying g_t by the SSP country population.

In our main analysis, we employ the growth-based damage function specification BHM SR [9] which integrates the

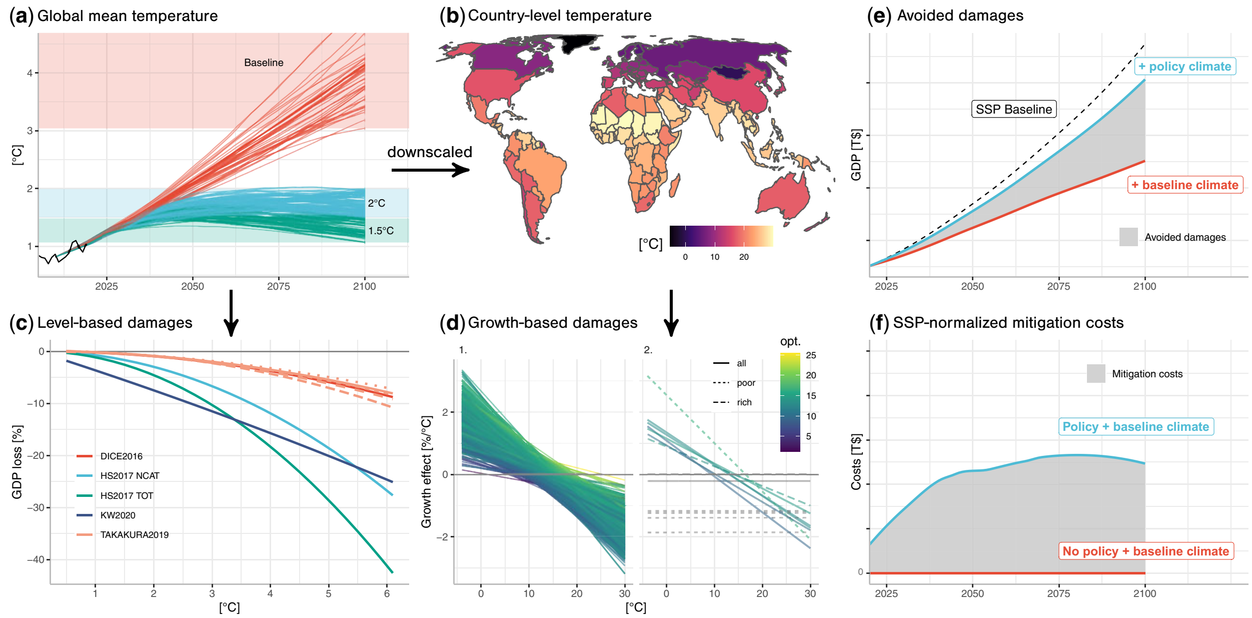

Figure 1: Methodology diagram. Model scenarios, with mitigation, are clustered into two groups: 2°C and 1.5°C, according to their global mean temperature in 2100. The baseline scenario, without mitigation action, and the SSP baseline scenario associated with the policy scenario are also identified. (**a**) The global mean temperature is downscaled to country level (**b**) and applied to global level-based damage functions (**c**). Country-level temperatures are applied to growth-damage functions in two different ways (**d**). The BHM SR damage function is applied using bootstrap regression coefficients [23] (d.1.) for our main analysis and many different specifications of damage functions from the literature for robustness check (d.2.). Avoided damages are the difference in GDP between the SSP baseline and policy with climate change (**e**). Mitigation costs, in T$, are rescaled to the SSP baseline GDP with climate change (**f**). Net benefits compare avoided damages and mitigation costs. The results of (d.1) are reported in the main analysis and those of (c) and (d.2) are reported in the robustness section.

regression uncertainty. We use the coefficients from 1000 bootstrap regressions of the BHM SR specification using the replication code from Ref. [27]. For this specification, gdp_{cc} is aggregated at the regional level and at the global level. For all other specifications, gdp_{cc} is aggregated at the global level.

Global and regional mitigation costs cmit are primarily translated into GDP percentage loss from the scenario database, then applied to the SSP baseline scenario with the warming effect gdp_{cc}. Mitigation costs compatible with a warming of a 1.5°C are higher and more uncertain than those at 2°C. The uncertainty about mitigation costs (the range across scenarios) increases with time (see Supplementary Fig. S2).

The net benefits of the scenarios are computed globally, for all specifications, and regionally, for our main specification BHM SR, relative to the GDP in the baseline scenario with climate change $\mathrm{gdp}^{\star}_{cc}$. Net present benefits are

$$\mathrm{NB} = \frac{\sum_{y=2020}^{2300} \gamma^{y-2020}(\mathrm{gdp}_{cc}y - \mathrm{cmit}_y)}{\sum_{y=2020}^{2300} \gamma^{y-2020}(\mathrm{gdp}_{cc}y^{\star})},$$

where $\gamma^y = \frac{1}{(1+r)^y}$ is the discount factor in the year y with the discount rate r. After 2100, the mitigation costs and the avoided damages are extrapolated constantly in our default setup (see Supplementary Methods).

To summarize, we account for uncertainties at different levels: the emission scenarios and their mitigation costs (including multiple IAMs and different underlying socio-economic narratives), the climate projections (including the climate sensitivity uncertainty and the climate model patterns), the damage functions (including the regression uncertainty for our main damage specification and a variety of specifications in the robustness analysis), and the discount rate.

RESULTS

The global net benefits of attaining well below 2°C are reported in Fig. 2a. At a 2% discount rate, our estimates of the net present value of the net economic benefit are 5.6% of baseline GDP with warming (−13.4% to 20.1%, 90% confidence interval) for the median estimates of the global mean temperature, 6.0% (−6.9% to 18.1%) and 4.9% (−28.5% to 25.2%) for the 5th and the 95th temperature percentile, respectively. Looking at the probability distributions which account for damage, climate and mitigation cost uncertainties, we find that the net benefits are not statistically significantly different from zero for all temperature percentiles. The overall result is qualitatively the same for different discount rates: at 1%, net benefits are of 8.8% (−17.5% to 32.3%, 90% CI) and at 3%, they are of 3.2% (−10.1% to 12.1%) for the median estimates of the global mean temperature (Supplementary Fig. S7).

If we compare the net economic benefits between the 1.5°C and 2°C scenarios, the two climate targets yield similar benefit–cost ratios (Supplementary Fig. S8). The additional benefits of reduced temperature compensate the extra mitigation costs of tightening the policy by half a degree, which are on average equivalent to 1.2% of baseline GDP. For a 2% discount rate, the median net benefits are 6.0% and 5.4% of basline GDP, respectively, for 1.5°C and 2°C, that is, the benefits of a lower temperature target are larger than the mitigation costs. There is not a clear relation between the temperature reached in 2100 and the net benefits, suggesting the importance of the temperature trajectory, unless we consider a low discount rate at 1% where the

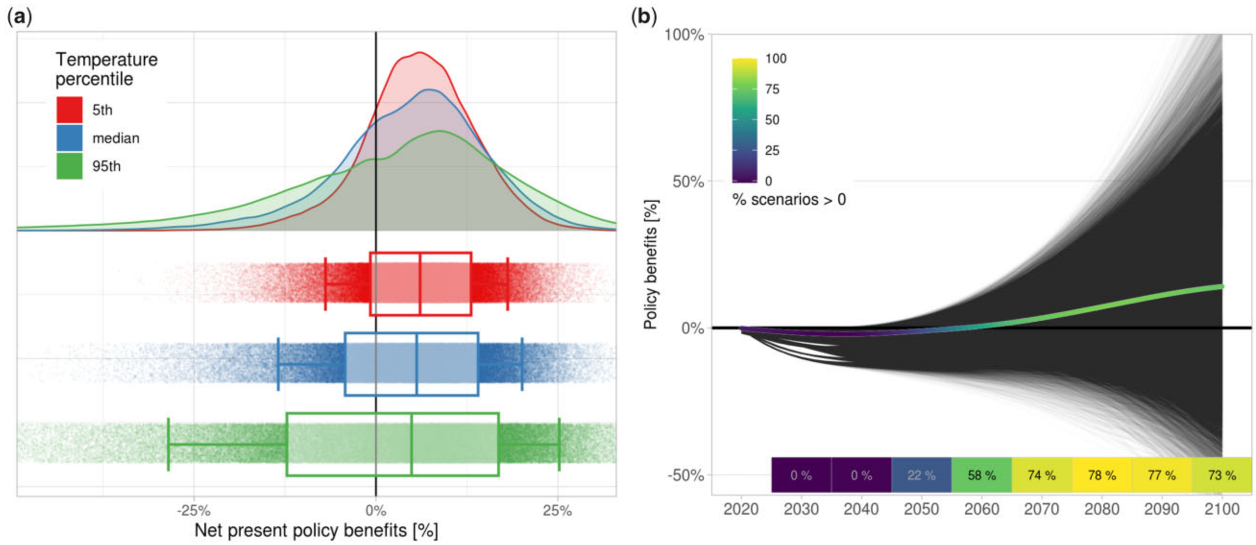

Figure 2: Distribution of global net economic benefits from mitigation of well-below 2°C scenarios. (a) The distribution of the net present values of the net economic benefits in 2020 using a 2% discount rate, expressed relative to the baseline GDP with warming (the density function in the upper part, jittered points and box plot in the lower part). The colour indicates the temperature percentile. The box plots represent the median, the 90% and 66% range of the distributions. (b) The annual net benefits for the median estimate of the global mean temperature. The coloured line highlights the median annual net benefits. The colour scale reflects the percentage of scenarios with positive annual net benefits. The numbers above the x-axis report this number every 10 years. Net benefits are computed for our main specification: the growth-based damage function BHM SR, using the 1000 bootstrap regression coefficients [27].

Table 1: Annual net economic benefits from mitigation of well below 2°C scenarios, expressed relative to the baseline GDP with climate change.

Temperature trajectory	2050	2100
Median	−1.1% [−6.3%; 1.5%]	15.3% [−9.5%; 48.5%]
5th	−0.9% [−6.0%; 1.5%]	15.0% [−22.0%; 59.3%]
95th	−0.5% [−5.4%; 3.1%]	14.8% [−41.6%; 93.6%]

The median value is reported along with the 90% confidence interval.

lower the temperature in 2100, the higher the net benefits (Supplementary Fig. S9).

Looking at the time profile of costs and benefits (Fig. 2b and Table 1), we find that most scenarios have net economic benefits after 2050 and the majority (>70%) by 2070. This reflects the different temporal dynamics of mitigation costs and benefits. We also explore the entire scope of the climate sensitivity and compute the results for low and high climate sensitivity (Supplementary Fig. S10). Comparing our results for changes in climate sensitivity, we find the dynamics are mostly affected after 2050. With a low climate sensitivity, the number of scenarios with positive net benefits goes from above 40% to 85%, while with a high climate sensitivity, this number remains in the range 60–80% with a decreasing number at the end of the century. This suggests the importance of exploring explicitly the time profiles of net benefits, rather than solely concentrating on the net present value.

Figure 3 shifts the focus to the geographical distribution of net benefits and shows how the global picture hides significant variations across regions. The non-linearity of climate impacts, as estimated by Burke *et al.* [9], implies enormous benefits for the hotter and poorer parts of the world. Mitigation costs depend on assumptions about the regional allocation of mitigation effort. Most scenarios reviewed by the IPCC assume an efficient allocation of effort, that is an allocation which minimizes global costs. For this reason, mitigation effort is higher in carbon-intensive economies with relatively lower marginal abatement costs. These regions are economies in rapid development and endowed with fossil fuels, as for example Middle East and the former Soviet Union [32]. Such allocation is not based on ethically based burden sharing rules and different *ex post* redistribution of costs could be defined based on international negotiations. The regional outcome is that the global south gains from climate stabilization across all scenarios by the end of the century and the highest benefits are concentrated in sub-Saharan Africa, and South and East Asia. OECD region's net benefits are slightly negative in 2100 for the 1.5°C and 2°C.

ROBUSTNESS

Given the uncertainties surrounding the estimates of economic impact, we perform the analysis with a large number of published estimates, but without including the regression uncertainty. A crucial distinction exists between 'level' and 'growth' damage functions. In the former, temperature is assumed to reduce economic output, while in the latter temperature affects economic growth. These two frameworks span the limiting cases, from full adaptive capacity to persistence of climate-induced economic impacts. Figure 4 reports the results under 25 damage functions specifications. Out of all scenarios, few entail net discounted benefits that are statistically negative; others imply benefits that are either not statistically different from zero or positive. In particular, at a 2% discount rate and over the 95% range of climate sensitivity uncertainty, for the 2°C scenarios, six damage functions find statistically significant net benefits (at 95% level). For the 1.5°C scenarios, five damage functions find significant net benefits (at 95% level). There are not large differences between the two temperature clusters. The reduction in damage, from 2°C to 1.5°C, is compensated by an increase in mitigation costs with a more or less important effect depending on the damage function.

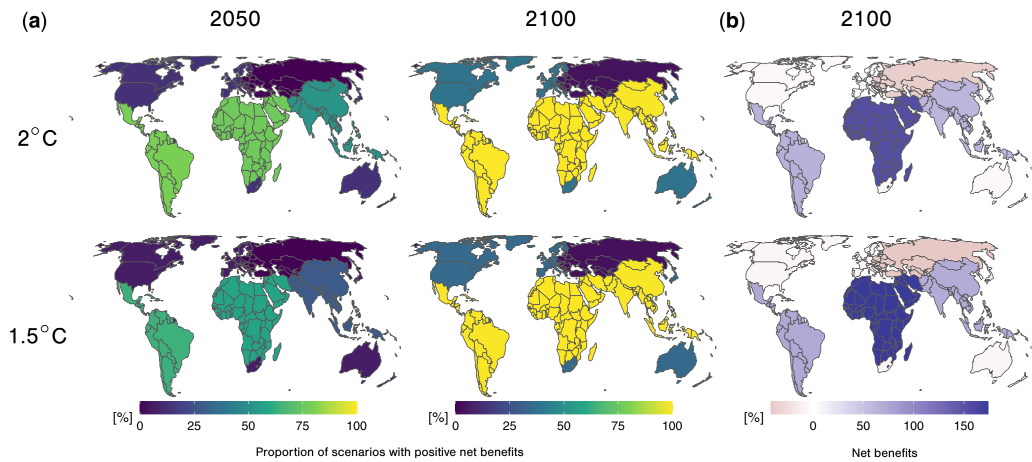

Figure 3: Regional net benefits from 2°C and 1.5°C climate policies. They are aggregated and compared using the five global regions as provided in the SR1.5C scenario database. (**a**) The share of scenarios with positive net benefits in years 2050 and 2100. (**b**) The net benefits relative to the baseline GDP with climate change in 2100. Net benefits are computed using with median estimate of the global mean temperature for our main specification: the growth-based damage function BHM SR, using the 1000 bootstrap regression coefficients [27].

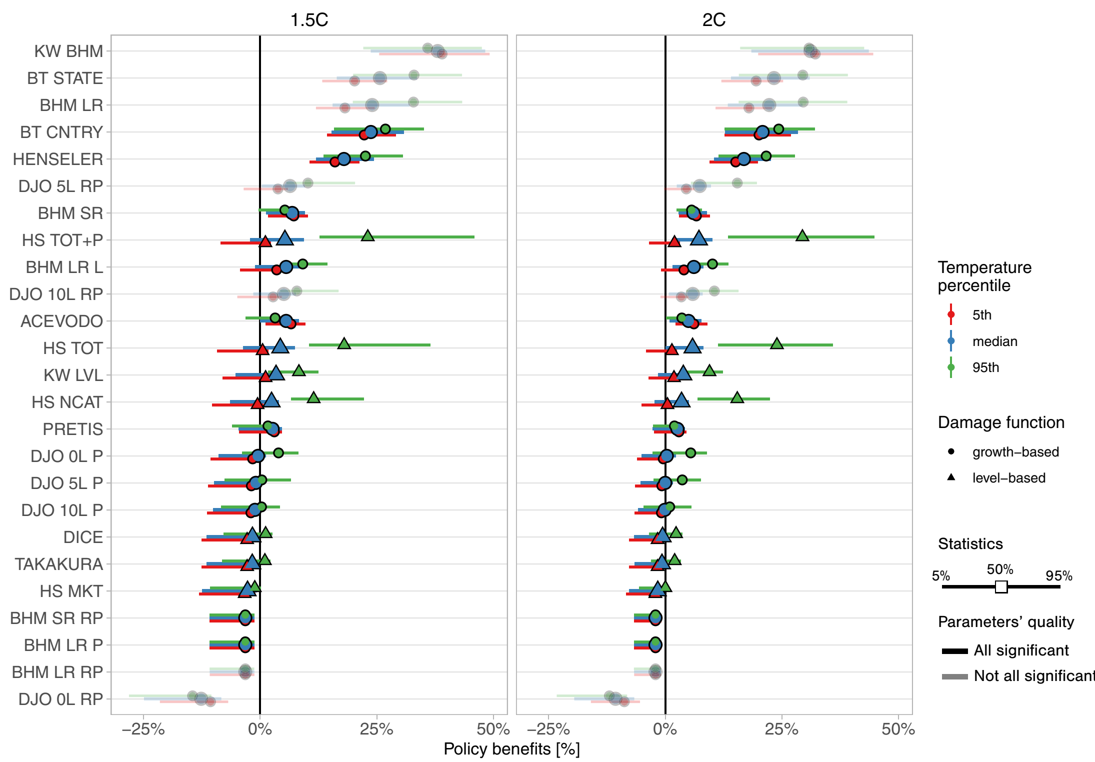

Figure 4: Influence of the damage function on the net present value of net benefits from 2°C and 1.5°C climate policies. Each error bars report the uncertainty range (5–95%) across scenarios. The middle points present the median. Damage functions are ranked according to the median value of the median temperature percentile. Growth-based and level-based damage functions are differentiated by the shape of the middle points. The colours indicate the temperature percentiles (5%, 50% and 95%), representing the climate sensitivity uncertainty. Damage functions with some non-significant parameters (*P*-value > 0.05) are transparent. Parameters of the damage functions are reported in Supplementary Tables S1 and S2.

We also consider different discount rates (Supplementary Fig. S11). At a 1% discount rate, we get similar results than for the 2% discount rate with one damage function ('HSM MKT') becoming non-significant on the negative side and 10 damage functions being significant at the positive side in the 2°C cluster (at the 95% level). At a 3% discount rate, five damage functions find significant net costs and five damage functions net benefits (at the 95% level). This also highlights the importance of inspecting the time dynamics of the net benefits, which vary a lot across damage functions. However, the trajectory of net benefits always curves upwards at the end of the century, but more or less quickly (Supplementary Figs S12 and S13).

The confidence intervals around the median values highlight the large uncertainties surrounding the estimates of the net economic benefits. These uncertainties are not only because of climate impact functions but also to the direct costs of reducing emissions. The macroeconomic repercussions of mitigation are also poorly understood, with different assessments providing different magnitudes of economic losses. These differences can be ascribed to assumptions about underlying economic frameworks and about policy design. Economic frameworks involving distortions in markets and innovation processes, as well as multiple market failures, foresee lower (and possibly even negative) economic costs than neoclassical ones [33]. Policy design also matters: the extent to which policies are harmonized across sources and countries, and how the revenues of interventions are used, can lead to very different economic implications of reducing emissions.

In Fig. 4, we treated all damage function specifications equally, but conclusions have to be drawn carefully, as the methodologies and the sector and impact coverage vary across damage functions. The panel-based damage functions cover only the market impacts, while it is more varied for the level-based damage functions built from enumerative methods or from a computable generable equilibrium model. Supplementary Table S1 reports the coverage of those functions. The damage function from Ref. [24] is built from a meta-analysis and can highlight the impact of the damage function coverage by using the various specifications. The more inclusive is the damage function, starting with market-only impacts, adding subsequently non-market impacts, catastrophic damages and productivity effect, the higher are the net benefits (Supplementary Fig. S14). This may suggest that the net benefits computed by level-based damage functions would be higher if additional impacts are considered, but the implications for those computed by the growth-based damage functions are unclear.

Another critical aspect about the net present values is the extrapolation of the net benefits after 2100, as most of the data from the climate models and the detailed process IAMs is provided until 2100. We show the implication of the interpolation for the avoided damages and the mitigation costs in Supplementary Fig. S15. The results are sensitive to how the avoided impacts are projected into the future. From the conservative assumption (constant extrapolation, our default one) to the more optimistic one (linear extrapolation), the net benefits shift towards the positive and this is much visible for the specification with significant net benefits. This shows that there are some knowledge gaps and efforts should be devoted to model the implications of climate policies after 2100, in particular if we consider low discount rates. After 2100, the impacts from sea-level rise could become prominent, the panel-based damage function, calibrated on historical observations, would be applied far out of the sample and the growth-based damage functions can be hardly used, as they are, over a long-time horizon.

Finally, we also look at the implication of time aggregation using a social welfare function. Going beyond the unique discount rate parameter, we compute the scenario welfare using the isoelastic Constant Relative Risk Aversion utility function and we compare their Certainty, Equity and Balanced Growth Equivalent (CEBGE) (see Supplementary Material for details). The policy benefits, expressed as the difference in CEGBE, are mostly positive for a range of a pure rate of time preference from 0% to 3%. Also, in the welfare analysis, the order of the damage functions is similar to the one in Fig. 4. One step further would be to look at the regional aggregation embedding the equity implication.

CONCLUSION

We have shown how to integrate economic costs and avoided damages from climate change using model scenarios. Overall, we find that despite large uncertainties, the current benefits and costs of attaining temperature goals of 1.5–2°C are of comparable magnitude and not statistically different from each other. We explored the asymmetric temporal and geographical distributions of benefits and costs, with benefits outweighing costs as time proceeds and developing countries exhibiting larger benefits.

Major uncertainties and caveats exist. On the climate damage side, the reviewed literature is based on historical relations which do not account for many sources of impacts. These include sea level rise and tipping points. Non-market damages are mostly not accounted for, despite their relevance [34]. Finally, co-benefits of mitigation pathways, such as improved air quality, which would accrue in the early years of decarbonization, are not accounted in these calculations. Mitigation costs are also uncertain, although arguably less than the economic impacts of climate change. Mitigation costs will depend on how emission reduction policies will be implemented and might even benefit GDP (e.g. when policies trigger large enabling infrastructure investments). Evidence drawn from existing carbon taxes points to zero to a modest positive impact on GDP and total employment growth rates [35], though much higher ambition in policies than what has been so far implemented is needed to achieve Paris consistent temperatures. Overall, the presented estimates of the net economic benefits of 1.5–2°C may be underestimated.

These results have important policy implications. They suggest that ambitious, but well coordinated, emission reduction strategies are worthwhile from a pure economic standpoint. The announced climate neutrality goals of several major economies are an important step forward, but are not enough to limit the temperature increase. Other countries, including developing economies, have a clear economic interest in keeping temperatures in check.

SUPPLEMENTARY DATA

Supplementary data are available at *Oxford Open Climate Change* online.

ACKNOWLEDGEMENTS

The authors thank the two anonymous reviewers for their valuable suggestions. They also thank the participants of the IAMC 2021 conference and the NAVIGATE/ENGAGE Expert Workshop for their feedbacks and comments.

STUDY FUNDING

This work has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement Nos 821471 (ENGAGE) and 821124 (NAVIGATE).

CONFLICT OF INTEREST

There is no competing interest.

AUTHORS' CONTRIBUTIONS

L.D., V.B. and M.T. designed the research. L.D. wrote the code and performed the simulations. L.D. and M.T. analysed the results and wrote and reviewed the manuscript.

DATA AND CODE AVAILABILITY

The IAMC 1.5°C Scenario dataset is available in Zenodo (https://doi.org/10.1038/s41558-018-0317-4). The SSP dataset is from https://tntcat.iiasa.ac.at/SspDb/dsd. The reproducible source code used for the data analysis and the figures can be found at https://github.com/lolow/iampact-ipcc-sr15c.

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