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LETTER

Disutility of climate change damages may warrant much stricter climate targets

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Abstract

Cost-benefit integrated assessment models (IAMs) inform the policy deliberation process by determining cost-optimal greenhouse gas emission reduction pathways based on economic considerations. These models seek to maximise economic utility and treat estimates of climate impacts (damages) and mitigation costs at par as GDP losses, having the same impact on utility reduction. However, prospect theory suggests that a certain level of climate damages could be valued higher by society than the same level of mitigation costs, as climate damages often occur as sudden unexpected events. In this paper, we show how this concept could be taken into account in cost-benefit IAMs and explore possible consequences on optimal mitigation pathways. Our results suggest that compared to the standard utility approach, capturing explicit aversion to climate impact incidence shows optimal pathways with earlier and deeper emission reduction, lowering both net-negative emissions and mid-century temperature peaks in line with stringent Paris Agreement targets.

Introduction

In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was established with the overall aim to prevent dangerous human interference with the climate system. In the Paris Agreement, the aim was made more concrete by the objective to keep the increase of global mean temperature change well below 2 °C by 2100 and to pursue efforts to limit it to 1.5 °C. Setting such a target and choosing appropriate mitigation strategies are extremely difficult given the complex web of socio-economic, technical, geophysical and ethical aspects that play a role and the multiple perspectives and interests. Integrated Assessment Models (IAMs) have played a key role in exploring the interplay of several of these factors to derive useful insights for policymaking. Broadly speaking, two main types of IAMs can be distinguished: process-based IAMs which focus on the required changes in technologies and behaviours to achieve certain climate targets and cost-benefit IAMs which focus on evaluating the costs and benefits of climate policy (Weyant 2017).

Many studies using cost-benefit IAMs have shown that cost-optimal climate targets are sensitive to damage estimates (Howard and Sterner 2017) and the social discount rate (Guo *et al* 2006, Arrow *et al* 2013). All these cost-benefit studies assume that the impact of climate change damage on utility can be assessed directly at par with the impact of mitigation costs—or economic loss due to any other reason—on utility. There are arguments why these costs should not be evaluated the same, as literature on prospect theory has shown that the disutility of losses is larger than the utility of the same value of gains (Kahneman *et al* 2011). While evidence for prospect theory is generated at the micro level, recent studies have found evidence that it also applies on the macro-level (Neve *et al* 2018).

Many mitigation measures are planned; the costs associated with these measures therefore do not come as a sudden surprise. The planned nature of mitigation is clear from the fact that 194 countries have submitted mitigation plans through the mechanism of Nationally Determined Contributions in the UNFCC process

(UNFCCC 2022). Additionally, 136 countries, 235 cities, and 683 companies have committed themselves to a net-zero emissions target by 2050 (Hale *et al* 2021, Climate Action Tracker 2022). Damages resulting from climate change, however, often come as a sudden loss with a large impact on local communities (think of storms, floods, droughts, wildfire). In this paper, we show how the concept of prospect theory could be applied in evaluating climate damages in cost-benefit IAMs and what the resulting impact of doing so could be on cost-optimal and cost-effective emission pathways.

For this, we use the MIMOSA model, based on a simple Ramsey economic growth model (van der Wijst *et al* 2021b). A production function is calibrated to socio-economic variables obtained from the Shared Socio-economic Pathways (SSPs). Estimates on mitigation costs and climate damage costs from recent literature are subtracted from this SSP-consistent baseline GDP as losses. The damage function developed in the COACCH project (hereafter the 'COACCH damage function') is employed for damage cost estimates (Schinko *et al* 2020). It accounts for uncertainty by defining the damage function to fit increasing quantiles of a broad range of sectoral estimates. The mitigation costs are calibrated to IPCC AR5 data. The utility of consumption in each period is derived from the GDP after mitigation and damage losses. Since mitigation (emission reduction) reduces expected damages, and both costs influence the utility equivalently at a given time, the model determines the least-cost trade-off between the two that maximises the discounted utility (welfare). The utility maximising model can be run either with a fixed cumulative end-of-century emission budget (or temperature target), or without. The first case represents a cost-benefit setting deriving the optimal pathway for a given temperature target, while the second constitutes a traditional cost-benefit analysis without any external temperature constraints.

Using this model, we implement a disutility that captures the loss aversion towards estimated climate damage costs. To do so, we first disaggregate the prospective loss of utility attributed to the estimated damage costs in each period. The disutility of damage is then calculated by multiplying it with a parametrised damage loss aversion factor. A loss aversion factor to 1 implies no additional disutility from climate damage similar to the standard utility approach, while values of 2 to 3 are analogous to mean loss aversion factors according to Prospect Theory literature (Tversky and Kahneman 1992; Wang *et al* 2017). While in standard cost-benefit analysis utility is derived from consumption only, our approach adds an extra dimension of disutility which does not depend on GDP or consumption, but on damages only. As in standard cost-benefit analysis, utility is then discounted to the present, and is optimised by the model as before. We analyse the relative impact of the damage aversion factor, as well as varying discount rates and damage estimates on the optimised temperature, emission, and carbon price pathway.

A more detailed description of the MIMOSA model and the disutility modelling is given in the Methods section.

Methods

The model

Figure 1 shows a simplified schematic overview of the predecessor MIMOSA model, and the modification made in this work to implement the disutility from damages. It consists of an economic module (top grey box) and an energy-emissions module (bottom grey box) that interact via the mechanisms of damage costs (middle, left), and mitigation costs (middle, right).

A standard Cobb-Douglas production function derives the GDP in the period, calibrated using total factor productivity and labour inputs derived from SSPs. This economic output is split into consumption and savings via a fixed savings rate. Savings are fully invested in the next time step as capital input to the production function. In the standard approach, utility is derived solely from the consumption in each time step, and is discounted to the present. The objective of the model is set to maximise the sum of the discounted utility in each time step, i.e. the welfare.

In parallel, the emissions module derives the CO_2 emissions as a function of endogenous GDP and exogenous baseline carbon intensity of the energy systems fuelling it. Emissions in each time step accumulate in the earth's atmosphere. Cumulative emissions cause a rise in the global mean temperature (GMT) modelled via a linear Transient Climate Response to Emissions (TCRE) relationship. The economic impact of rising GMT is modelled as a damage function, and is treated as a GDP loss in the time step. These climate change impacts are mitigated by reducing annual emissions. A global carbon price is applied at each time step. An exogenous Marginal Abatement Cost (MAC) curve calibrated based on data presented in IPCC's Assessment Report 6 (AR6)[4] is used to determine the corresponding reduction in emissions and quantify the mitigation costs in the

[4] The MAC curves are based on figure 3.34c of the IPCC AR6 WGIII report that plots discounted consumption losses from mitigation as function of cumulative CO2 emissions. This means the MAC curves are a result of all scenarios from a wider range of models from the AR6 database. The underlying models all differ in their exact definition of mitigation costs; Annex III.I.9 (p. 1863 - 1869) of the same IPCC report provides a summary of key characteristics of these models. See Supplementary Information section (SI.4.1) in van der Wijst *et al*, (2023) for more details on the calibration method used in the predecessor model.

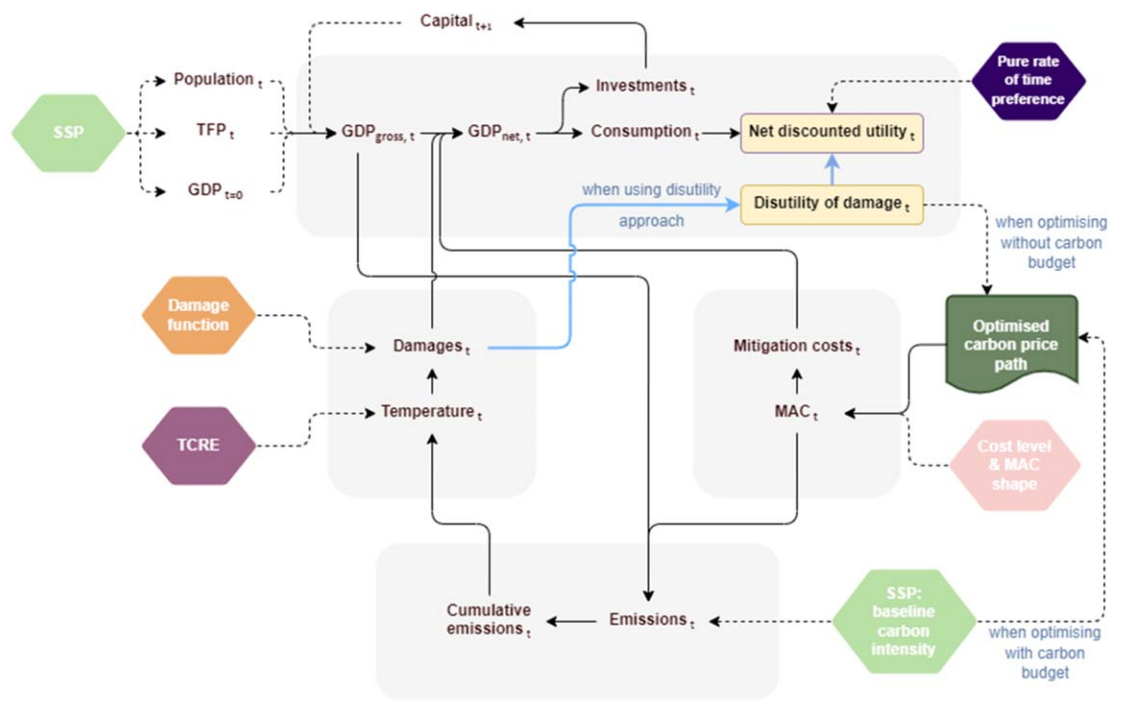

Figure 1. Schematic overview of the MIMOSA model with the novel disutility approach, adapted from (van der Wijst *et al* 2021b).

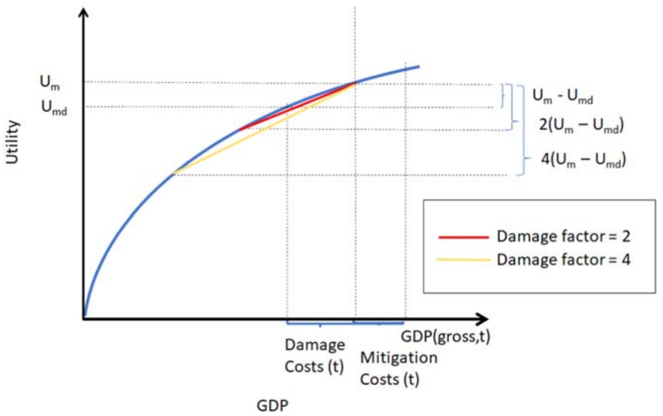

Figure 2. Stylied representation of unequal utility of consumption and disutility of damage.

time step. These costs are treated as a GDP loss similar to damages, reducing the net GDP and consumption in the time step, and causing a drop in the utility. A more detailed description of the predecessor model, including the data sources, parametrisation choices, and other assumptions can be seen in (van der Wijst *et al* 2021a, van der Wijst *et al* 2023).

Figure 2 shows a stylised representation of the disutility of damage with respect to the standard concave utility function with respect to GDP (assuming a fixed savings rate). 'U_{md}' is the utility derived from GDP less the mitigation and damage costs, equivalent to the net utility in the standard approach. Analogously, 'U_m' is the utility derived from the baseline GDP less mitigation costs alone. The disutility of damage is calculated as the prospective loss of utility attributed to the estimated damage costs (i.e. U_m—U_{md}) times a parametrised damage loss aversion factor (f_d). The net utility is then given by:

$$U_{net} = \quad U_m - f_d(U_m - U_{md})$$

Modifications to the predecessor model to implement the disutility approach involve deriving this net utility which is discounted and optimised as with the standard approach.

When the model is run with the standard utility approach, the drop in the net utility is the same irrespective of the source of GDP loss. When the model is run with the disutility setting, both damages and mitigation costs

Table 1. Model inputs and their value ranges over which the model runs are performed.

Input variable	Range	Units
Welfare function	[without disutility, with disutility]	n/a
Damage loss aversion factor (when run with disutility)	[2, 3]	n/a
Carbon budget	[None, 1344, 633]	$GtCO_2$
COACCH damage function specification	[5, 25, 50, 75, 95]	Percentile
Pure rate of time preference	[0.1, 1.5, 3]	% per year

still have the same effect on the GDP itself. However, their respective impacts on the net utility are disaggregated. Mitigation costs continue to have the same effect on consumption utility as in the standard approach, while damages affect net utility through the separate disutility.

The damage loss aversion factor represents the degree of loss aversion towards climate damage. Since a loss aversion factor set to 1 implies no additional disutility from climate damage, model experiments are carried out by parametrising its value to 2 and 3 for analysis in this paper (table 1), reflecting the range of the mean loss aversion factor in prospect theory literature (Tversky and Kahneman 1992, Wang *et al* 2017). Further research can experiment with different values for the damage aversion factor.

Experimental methods and setup

We run the model with welfare functions specified to include the disutility approach and with the standard utility approach of the predecessor model. Additionally, model runs are also performed by varying the damage loss aversion factor as well as with different values for the carbon budget, damage function specification and discount rate—or more specifically, the pure rate of time preference (PRTP). A summary of the variables and values is shown in table 1 below. Outcomes are retained for analysis for the full factorial of these input combinations.

This allows us not only to perform an analysis of the outcomes under different input combinations, but also lets us determine the influence of the disutility approach and its parametrisation on the outcomes relative to that from higher damage estimates and a range of discount rates (see SI.1 in the supplementary information for a variance-based sensitivity analysis of model outcomes, and SI.5 for model estimates for mitigation and damage costs in for scenarios with and without disutility).

Results

Cost-optimal outcomes (i.e. without a carbon budget) with the standard utility approach using a discount rate of 1.5% and the median (50th percentile) COACCH damage estimates are shown in blue in figure 3. The global mean temperature rises throughout the century, reaching 1.78 °C by 2100, as also shown by van der Wijst *et al* (2021a). The corresponding optimal cumulative emissions reach 1119 $GtCO_2$, with a greater reduction of annual net emissions up to 2035, and a more gradual reduction after. Net-zero emissions are achieved only in the first half of the 22nd century in this optimal pathway, i.e. beyond the modelled timeframe.

The orange lines in figure 3 show the impact of valuing the disutility of damages higher than the disutility of mitigation costs by a factor 2. Optimal cumulative emissions up to 2100 are reduced by about 43% to 634 $GtCO_2$ with the disutility approach without carbon budget constraints. Net annual emissions follows a smoother reduction pathway compared to the standard approach with deeper initial mitigation until 2040. This corresponds to a drop in temperature rise at 2100 from 1.78 °C to 1.49 °C, with a temperature peak at 1.5 °C.

For a loss aversion factor of 3 (figure 3, outcomes in green), cumulative emissions are reduced even further to 327 $GtCO_2$. Temperature rise by the end of century is 1.29 °C, reducing from a peak of 1.39 °C in 2065. Net-zero CO_2 emissions are achieved in 2065 in this case, compared to 2085 for an aversion factor of 2.

The effect is further emphasised with higher estimates for uncertain damages implemented via the COACCH damage function (Schinko *et al* 2020) using a set of quantile specifications (figure 4). The 5th percentile of this independently derived function closely resembles the low range of damage functions in literature (such as the DICE 2016R2 damage function (Nordhaus and Moffat 2017)), the median 50th percentile resembles the medium range (based on a meta-analysis by Howard *et al* of empirical and traditional IAM estimates (Howard and Sterner 2017)), while the 95th percentile nears the high range of estimates in literature (long-run empirical damage function from Burke, Hsiang and Miguel (Burke *et al* 2015)). This allows us to capture the range of possibilities by varying the specifications for a single function (van der Wijst *et al* 2021a).

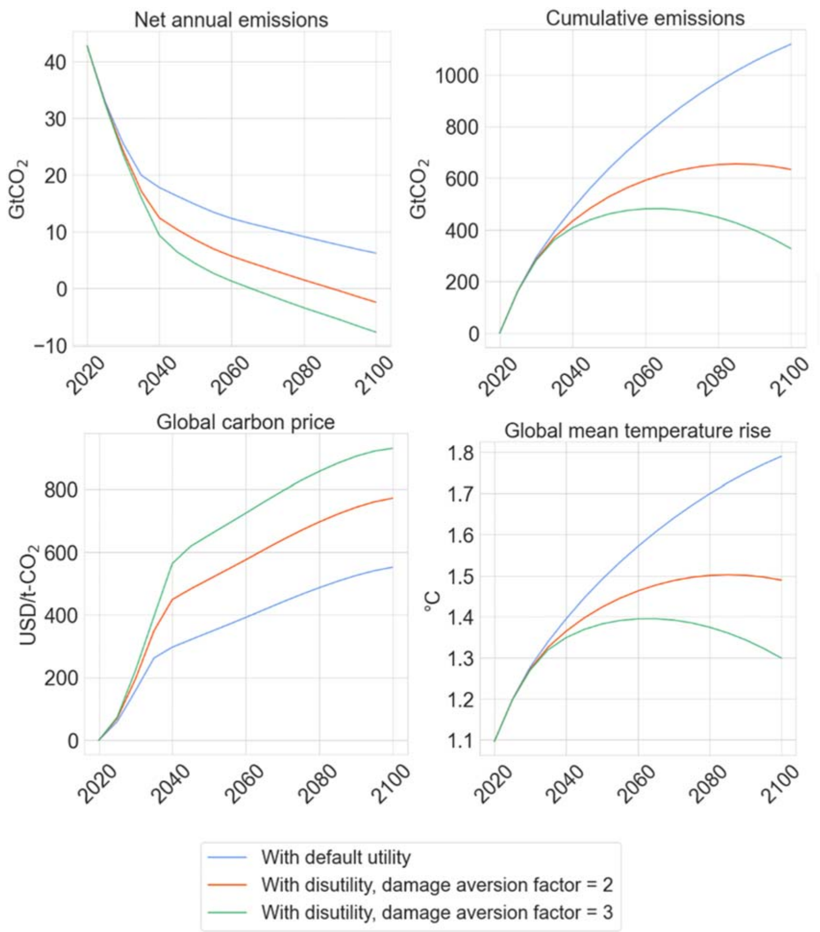

Figure 3. Optimal pathways without carbon budget constraints with and without the disutility approach. Panels, a: net annual emissions, b: cumulative emissions, c: population-weighted global carbon price, d: global mean temperature rise.

For low estimates of damages (the 5th percentile of the COACCH damage function), optimal end-of-century temperature change is reduced from 2.8 °C in the standard utility approach to 2.6 °C in the disutility approach (aversion factor 2). However, a similar aversion towards medium to high damage estimates leads to a sharp advancement in the optimum timing of zero annual emissions, leading to end of century temperature rise of 1.5 °C and 1.2 °C respectively. The impact of the disutility approach is highlighted by similar optimal temperature outcomes for the 95th percentile of the damage estimate optimising for the standard utility, as for the median damage estimate with disutility using an aversion factor 2.

The impact of disutility can also be illustrated by analysing its effect on temperature-constrained cost-optimal emission pathways. If the carbon budget is fixed at 633 $GtCO_2$, implying an end-of-century temperature increase of 1.49 °C in line with Paris Agreement targets, the disutility approach leads to deeper short-term emission reductions compared to the standard approach for the same cumulative target (figure 5), leading to lower peak emissions; with correspondingly lower peak temperature rise and earlier net-zero targets.

The optimal mitigation pathways using the disutility approach is reflected by higher initial rates of increase in the global carbon-price followed by a slower rate culminating in a peak or level price by 2100 (figure 5(c), in orange). In comparison, the standard utility approach (figure 5(c), in blue) shows a preference for delayed deep mitigation. Correspondingly, a lower initial increase in the carbon price is followed by a steeply increasing rate across the century. This culminates in a carbon price at 2100 that is higher than with the disutility approach, and which continues to peak beyond the modelled timeframe.

The above illustrates that taking into account the possibility that disutility of damages valued more strongly than the disutility of mitigation costs can have a strong impact on the optimal peak temperature and emission pathway. A simple sensitivity analysis (methodological details and results presented in Supplementary Information) confirms that this impact from capturing loss aversion preferences is comparable to that from varying rates of time preference through discounting.

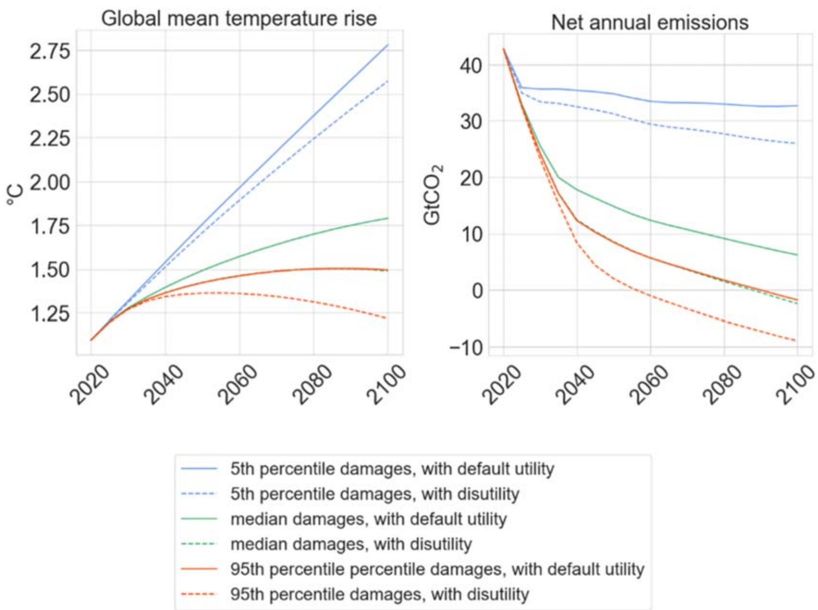

Figure 4. Optimal pathways with different damage estimates with and without the disutility approach. Panels, a: temperature, b: annual emissions. See SI.3 in Supplementary Information for optimum pathways constrained with a carbon budget across damage estimates.

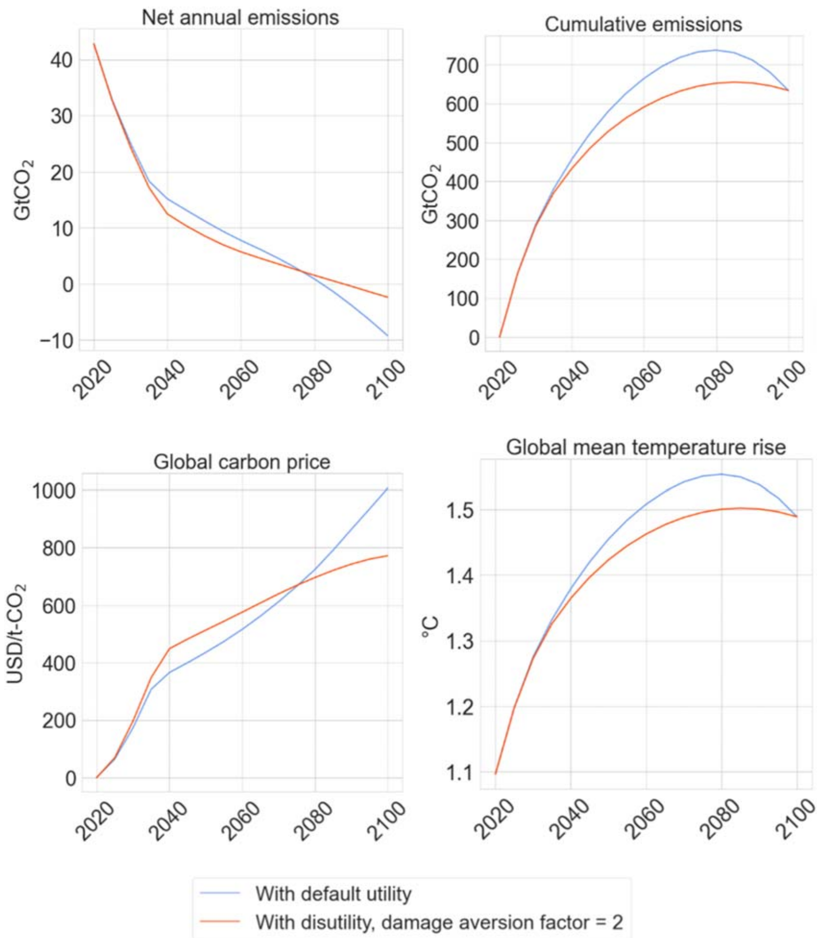

Figure 5. Optimal pathways with a fixed carbon budget of 633 $GtCO_2$. Panels, a: net annual emissions, b: cumulative emissions, c: population-weighted global carbon price, d: global mean temperature rise. See SI.2 in Supplementary Information for optimal pathways including with an aversion factor 3, and also with a carbon budget of 1344 $GtCO_2$.

Discussion

Cost-benefit IAMs inform the policy deliberation process by determining optimal emission pathways based on economic considerations and estimates of climate impacts and mitigation costs. The outcome of these studies hinges critically on the evaluation of macroeconomic consequences of potential climate change impacts (damages), which are always treated at par with the costs of mitigating them. While this parity has been unchallenged as of yet, prospect theory shows—at least the micro level—that this is not necessarily the best way to evaluate costs and benefits of climate change, as the costs of mitigating climate change are more predictable than the impact of damages. Mitigation is mostly planned, meaning that the costs of mitigation measures come less sudden and by surprise than incidence of climate change damages. This does not mean that actors do not experience utility loss from specific mitigation measures (e.g. closure of coal mines, increased household energy expenditure). However, these losses could be anticipated, and individuals could be compensated via social protection programs, re-skilling, etc. While it could be argued that uncertainty in mitigation costs is currently underrepresented in scenarios because extremes are not well taken into account, these extremes could still be located, analysed and internalised in models as the modelling community moves ahead with improved tools and strategies at their disposal (McCollum *et al* 2020). Therefore, they involve a greater degree of control and possibility of alternatives for policymakers than deeply uncertain incidence of damages that are inflicted on society without much control on the nature degree and distribution. In the latter case, only ex-post compensation measures are available, e.g. through insurance.

The disutility approach described in this article challenges the parity between mitigation costs and damages and offers a method to express the trade-offs between them in an intuitive, comparable way in a quantitative economic cost-benefit paradigm. It provides a mechanism to express social preferences specifically towards averting climate impacts (such as those reflected in the Paris Agreement or net-zero pledges by 2050), and to determine acceptable trade-offs. This work does not give a new generalised formulation for the welfare utility function. Instead, it highlights that economic notions of utility depend not just on monetary costs, but assumptions on social preferences towards the outcomes. The most commonly accepted form of the utility function is modified to accommodate aversion preferences towards the incidence of climate change impacts within the purpose of cost-benefit IAMs.

Prior studies assessing the suitability of prospect theory to climate cost-benefit studies find merit in doing so to gain specific insights, and not as a replacement of the standard expected utility theory (Osberghaus 2017). Reference dependence makes prospect theory outcomes contingent to context and problem framing. Expected utility theory, which is based on consumption levels rather than losses and gains does not share this problem.

The Representative Agent in prospect theory has defined domains of gains and losses relative to their reference point at each time step, with distinct utility (or 'value') functions in each domain. The RA can be said to exhibit loss aversion behaviour when the value function in the domain of losses are steeper than that in the domain of gains , the extent of which is determined by a parametrised loss aversion factor relating the two functions. Thus, the Representative Agent loses greater marginal utility in the domain of losses than the gain in marginal utility from a nominally equal change in the domain of gains. This gives us a useful theoretical framework to accommodate the preferences to avoid climate damages. In the present study, the domain of losses is defined by the damages towards which the Representative Agent is posited to exhibit loss aversion preferences. The domain of gains is defined by consumption levels.

Choosing appropriate values for the degree of loss aversion poses a challenge. The original theory tried to estimate this parameter using elicited preferences based on relatively low-stakes choices presented to individual actors, and estimated an aggregate value for the parameter at 2.25 (Tversky and Kahneman 1992). Recent advances, however, find empirical evidence of loss aversion at aggregate macroeconomic scales with the degree of loss aversion varying across countries from 1.1 up to 5 (Wang *et al* 2017, Foellmi *et al* 2019, Hovi and Laamanen 2021). The implementation presented thus makes a conservative choice with chosen loss aversion factor values 2 and 3 (table 1), without taking a normative position on the choices.

Therefore, despite reference dependence challenges and micro origins, implementing loss aversion from prospect theory allows us create plausible stylized what-if scenarios consistent with common practice in IAMs.

Capturing loss aversion to climate impact incidence shows optimal emission pathways with deeper front-loaded emission cuts, and consequentially, a reduced dependence on negative emissions towards the end of the 21st century compared to the standard utility approach. This reduced dependence is particularly significant given the nascent technological know-how and capability to implement the negative emissions at the required time and scale per the standard approach. Optimal emission pathways using the disutility approach also lead to a lower peak temperature rise over the century and thereby lower unmitigated climate change damages. The temperature outcomes are consistent with the most stringent objective of the Paris Agreement for reasonable aversion factors and median damage estimates.

Further research could also explore the consequences of applying the disutility approach on regions, and further on within regions. It is well known that poorer countries are more vulnerable to climate damage compared to richer countries (Tol *et al* 2004; Posner and Sunstein, 2008; de Cian *et al* 2016), and further disproportionately on the poorest within countries (Hallegatte *et al* 2015). Apart from the aggregated assessments of optimal emissions pathways, the disutility approach can also be used to address distributional concerns by incorporating the unequal incidence of climate impacts as seen in (Dennig *et al* 2015), with explicit representation of aversion towards them.

Finally, alternative functional formulations of the disutility may also be explored further, such as by a convex (marginally increasing) function of accumulated damages with appropriate parametrisation of preferences to define the degree of convexity (Dietz and Stern 2015). Such a formulation may be better suited for the assessment of long term, intergenerational 'endowments' of climate impacts from choices made in the present, in addition to the resource and capital endowments associated typically with discounted utility-growth models.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Code availability

The full model code is available at https://github.com/shkulk/MIMOSA-Disutil.

Data availability

SSP data used in this article is available at the IIASA SSP database: https://tntcat.iiasa.ac.at/SspDb/. Data for the model runs and for the figures are available at https://github.com/shkulk/MIMOSA-Disutil.

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Conflict of interest

The authors declare no competing interests, have no related manuscripts under consideration elsewhere nor had any prior discussions with Nature Climate Change editors about the work presented in the manuscript.

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