Damage Functions and the Social Cost of Carbon: Addressing Uncertainty in Estimating the Economic Consequences of Mitigating Climate Change

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Abstract

Mitigating the effects of human-induced climate change requires the reduction of greenhouse gases. Policymakers must balance the need for mitigation with the need to sustain and develop the economy. To make informed decisions regarding mitigation strategies, policymakers rely on estimates of the social cost of carbon (SCC), which represents the marginal damage from increased emissions; the SCC must be greater than the marginal abatement cost for mitigation to be economically desirable. To determine the SCC, damage functions translate projections of carbon and temperature into economic losses. We examine the impact that four damage functions commonly employed in the literature have on the SCC. Rather than using an economic growth model, we convert the CO_2 pathways from the Representative Concentration Pathways (RCPs) into temperature projections using a three-layer, energy balance model and subsequently estimate damages under each RCP using the damage functions. We estimate marginal damages for 2020–2100, finding significant variability in SCC estimates between damage functions. Despite the uncertainty in choosing a specific damage function, comparing the SCC estimates to estimates of marginal abatement costs from the Shared Socioeconomic Pathways (SSPs) indicates that reducing emissions beyond RCP6.0 is economically beneficial under all scenarios. Reducing emissions beyond RCP4.5 is also likely to be economically desirable under certain damage functions and SSP scenarios. However, future work must resolve the uncertainty surrounding the form of damage function and the SSP estimates of marginal abatement costs to better estimate the economic impacts of climate change and the benefits of mitigating it.

Keywords Cost-benefit analysis · Climate modeling · Social cost of carbon · Marginal abatement costs · Carbon tax

Introduction

With reduction of CO_2 emissions necessary for mitigation of human-induced global warming (IPCC 2021), the social cost of carbon (SCC) is one of the most important concepts in the economics of climate change. Since it refers to the marginal damage from CO_2 emissions, policymakers use estimates of the SCC to inform decisions on mitigation strategies, such as the choice of a carbon tax. For a mitigation strategy to be economically feasible, the SCC must be greater than the marginal abatement cost of mitigation. Most SCC estimates in the literature come from one of three well-known integrated assessment models (IAMs): William Nordhaus' Dynamic Integrated Climate and Economics (DICE) model (Nordhaus 2014, 2018); Richard Tol's Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model (Tol 2019a); and Chris Hope's Policy Analysis of the Greenhouse Effect (PAGE) model

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(Hope 2013).[1] These IAMs assume a "damage function" that relates changes in temperature or, in some cases, changes in the atmospheric concentration of CO_2, to economic losses. One problem is that "the damage functions used in most IAMs are completely made up, with no theoretical or empirical foundation" (Pindyck 2013, p. 868). Further, there remain deficiencies in both theory and the data necessary to determine with confidence the relationships between climate/CO_2 and economic losses (Auffhammer 2018; Pindyck 2013), even though damage functions are crucial for estimating the SCC and informing climate policy. The purpose of the current study is to provide an alternative perspective on the sensitivity of the SCC to different damage functions.

The calculation of climate damages, and thereby the calculation of the SCC, depends on two relationships: (1) between emissions and a climate variable (usually temperature), and (2) between the climate variable and damages. To determine the first relationship, we use emissions data from four Representative Concentration Pathways (RCPs) developed by the International Institute for Applied Systems Analysis (IIASA) for the Intergovernmental Panel on Climate Change (IPCC)—these constitute a range of plausible emission projections.[2] The emissions data are then inserted into a three-layer energy balance model (EBM) that links CO_2 emissions to temperatures, providing projections of temperatures out to the year 2500.

The second relationship needed to estimate the SCC is between climate and economic damages. Four damage functions have been proposed in the literature by (1) Nordhaus (2014, 2017, 2018); (2) Weitzman (2010); (3) Golosov et al. (2014); and (4) Burke et al. (2015).[3] (1) In the DICE model, Nordhaus (2017) assumes that economic damages are a quadratic function of temperature. (2) In an adaptation of Nordhaus' damage function, Weitzman (2010) and Ackerman and Stanton (2012) assume damages increase exponentially for very high increases in temperature. (3) Golosov et al. (2014) employ the stock of atmospheric carbon, rather than temperature, to approximate damages, assuming that the convexity of the climate-damages relationship exactly offsets the concavity of the emission-climate relationship. (4) Finally, Burke et al. (2015) employ estimates of temperature's effect on economic growth. Using temperature and carbon projections from the EBM and RCPs, we provide estimates of the SCC based on each of the four damage functions. We denote the damage functions by their first authors; thus, the Nordhaus,

Weitzman, Golosov and Burke damage functions, respectively.

In addition to investigating the sensitivity to choice of damage function, we also compare projections of the SCC across RCPs to determine whether emission reductions beyond those provided in an RCP scenario are economically beneficial. This is done by comparing the SCC against estimates of marginal abatement costs. We will refer to the marginal abatement cost as the "carbon price", which is determined by the integrated assessment models that underlie the Shared Socioeconomic Pathways (SSPs). That is, the marginal abatement costs (=carbon prices) are provided in the SSPs for each RCP scenario—they are exogenously given.

Unlike previous IAM studies (such as Tol 2019b), we do not directly use DICE, FUND, or PAGE to estimate the SCC. Instead, we use scenarios derived from IAMs as inputs for our climate model, calculating damages separately. We do this because the IAMs determine the RCPs and SSPs that are used to inform the IPCC's climate models, and as such already optimize economic wellbeing (welfare in economic terms). By running the scenarios through a carbon-climate model and damage functions separately, we follow more of an integrated modular approach as recommended by the National Academies of Sciences, Engineering, and Medicine (2017). Decisions concerning optimal mitigation, consumption and investment are already present in the scenarios, so we do not attempt to calculate these variables.

The remainder of the paper is structured as follows. In the next section, we discuss the RCP emission scenarios and the climate sensitivity parameter. We then provide a brief description of the carbon-climate EBM, followed by an overview of the four damage functions, which includes a discussion about global output projections and calculation of the social cost of carbon. Then we present our results, followed by implications for policymakers. We end with some conclusions.
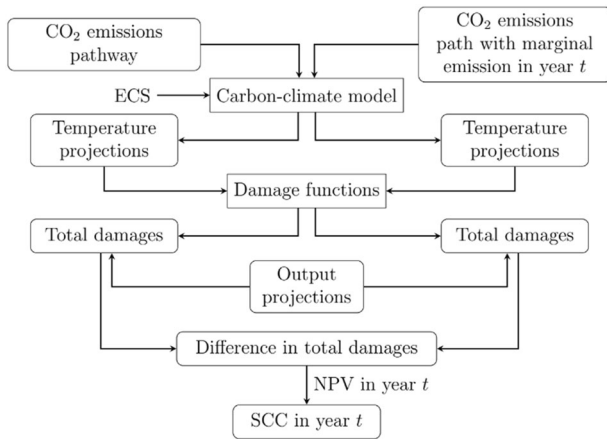
Modeling Emission Scenarios and Climate Sensitivity

Figure 1 summarizes the steps taken to calculate the SCC. We begin by inputting a particular emissions pathway into a carbon-climate model (Section 3), which leads to projections of future temperature. Using the temperature and carbon projections, we calculate damages as a proportion of global output using the various damage functions and obtain total damages by combining proportional damages with projections of global output. We then add one tonne of CO_2 (tCO_2) in a specified year, the "base year", to the emissions pathway used to calculate damages. The differences

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Fig. 1 Overview of methodology: steps to estimate the social cost of carbon

Fig. 2 Projected Annual CO_2 emissions (Gt) under the Representative Concentration Pathways (RCPs)
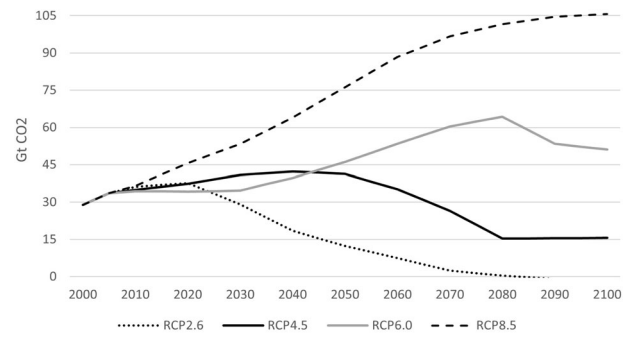
between the two paths of damages is the marginal damage from CO_2 emissions in the base year, or the SCC for that year. For example, the SCC for 2020 is determined by adding one additional tCO_2 in 2020 and comparing the discounted path of damages to those of the unperturbed trajectory. Ultimately, we separately project the SCC for every tenth year from 2020 to 2100.

To reiterate, an important distinction of our approach is that we do not directly use the DICE model or any other IAM to estimate the SCC, relying instead on information provided by the RCPs and SSPs. Data from various RCP/SSP scenarios are inputted into a carbon-climate model (described below), followed by the calculation of damages.

Emission Scenarios

We use the four RCPs developed in preparation for the IPCC's Fifth Assessment Report (AR5) as our emission scenarios. They provide a range of plausible emission forecasts as inputs to climate models to assess the implications of different climate outcomes (van Vuuren et al. 2011).[4] The RCPs were each derived by separate IAM modeling teams using different scientific, technological and economic assumptions. They include one scenario with low emissions (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high emissions (RCP8.5) (IPCC 2013, Chapter 1). The number attached to each RCP indicates the radiative forcing (in W/m^{2}) in year 2100, where radiative forcing is the difference between incoming solar radiation and the longwave energy radiated back to space—effectively the net radiation absorbed by the Earth's surface and atmosphere. Pathways with higher

radiative forcing, such as RCP8.5, lead to greater warming than pathways with lower radiative forcing, such as RCP2.6. Figure 2 plots the CO_2 emissions under each scenario.

Many studies estimate the SCC based on RCP8.5 alone (Hausfather and Peters 2020). In contrast, we estimate SCCs for all four of the RCPs identified earlier, because one should consider a range of scenarios, particularly considering possible mitigation strategies and changes to future policy. One can draw several insights from this approach. First, it is possible to analyze the sensitivity of the SCC to the assumed emissions pathway. Second, by comparing the estimated SCC to estimates of the marginal abatement cost (carbon price) required to reach a given RCP, it is possible to determine whether the emissions level in each RCP is close to the social optimum. Last, estimating the SCC of more than one emissions scenario helps capture some of the uncertainty in projecting emissions.

Climate Sensitivity

One factor that greatly influences temperature projections and SCC estimates is the equilibrium climate sensitivity (ECS), defined as the change in surface temperature that would occur if the concentration of atmospheric CO_2 was doubled. The choice of ECS strongly influences the estimated SCC, with a higher ECS implying a higher SCC.

There are two approaches to estimating the ECS. One is to employ complex climate models that simulate a doubling of CO_2 concentrations and then calculate the change in temperature after allowing the atmosphere and oceans to adjust. Using this approach, the likely range of ECS per the IPCC's physical science basis for the Sixth Assessment Report is 2.5–4.0 °C, with a best estimate of 3 °C. Values below 2 °C and above 5 °C are deemed low-likelihood values (Arias et al. 2021). This range is narrower than Fifth Assessment Report (AR5; IPCC 2013)

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[4] The RCP scenarios were used as inputs into climate models for the fifth Coupled Model Intercomparison Project (CMIP5), which then formed the basis of AR5.

range of 1.5–4.5 °C, which was first provided by Charney (1979).

The other approach to estimating the ECS is to use observational data and empirical methods. Observed ECS estimates are consistently lower than climate model estimates, the median averaging between 1.5 to 2.0 °C, as compared to 1.5 to 4.5 °C for the climate model estimates (Connolly et al. 2020).

To address the apparent discrepancy between observed and simulated ECS, we analyze several plausible values: (1) a median estimate of 3.1 °C used by Nordhaus (2017) in the DICE model and agreeing with the most likely value reported in IPCC (2021); (2) a low value of 1.8 °C that is within the range found in empirical studies (e.g., Lewis and Curry 2018; Pretis 2020); and (3) a high value of 5.3 °C used by one of the CMIP6 models (Gettelman et al. 2019).

Carbon and Climate Model

To determine the temperature projections under each of the four RCPs, we use a simple carbon-climate model, or energy balance model (EBM), which borrows the basic structure of the carbon and climate modules in DICE but employs our own calibrations (van Kooten et al. 2021). To ensure climate projections that are consistent with the CMIP5 ensemble, we calibrate the parameters of the EBM to match the temperature projections of the CMIP5 ensemble average, rather than using previously published values. Our model can be thought of as a simple climate emulator (see Curry 2021; Connolly et al. 2020).

Carbon Cycle

Our model has three carbon pools—the atmosphere, upper ocean and deep ocean——with carbon exchanged between adjacent layers:

$$M_{A,t} = E_{t-1} + (1 - \phi_{AU})M_{A,t-1} + \phi_{UA}M_{U,t-1} \quad (1)$$

$$M_{U,t} = (1 - \phi_{UA} - \phi_{UD})M_{U,t-1} + \phi_{AU}M_{A,t-1} + \phi_{DU}M_{D,t-1} \quad (2)$$

$$M_{D,t} = (1 - \phi_{DU})M_{D,t-1} + \phi_{UD}M_{U,t-1} \quad (3)$$

$M_{R,t}$ is total carbon in reservoir R at time t, with $R = \{A, U, D\}$; A refers to atmosphere, U to upper ocean, and D to deep ocean; E_t are total emissions at time t and $\phi_{i,j}$ is the fraction of carbon transferred between reservoirs i and j in a given time step; $(1-\phi_{i,j})$ represents the amount of carbon retained in reservoir i during the given time step (ϕ_{ii}). The values for $\phi_{i,j}$ used in the current study are in Table 1.

Table 1 Carbon cycle parameters

Parameter	Calibrated Value
ϕ_{AA}	0.9771
ϕ_{AU}	0.0229
ϕ_{UA}	0.0090
ϕ_{UU}	0.9899
ϕ_{UD}	0.0011
ϕ_{DU}	0.00005
ϕ_{DD}	0.99995

Source: van Kooten et al. (2021)

Climate

The following describe the temperatures of the atmosphere and the deep oceans across time:

$$T_t = T_{t-1} + \frac{\Delta t}{C_{up}}\left[F_{t-1} - \lambda T_{t-1} - \beta\left(T_{t-1} - T_{t-1}^{deep}\right)\right] \quad (4)$$

$$T_t^{deep} = T_{t-1}^{deep} + \frac{\beta \Delta t}{C_{deep}}\left(T_{t-1} - T_{t-1}^{deep}\right) \quad (5)$$

T_t (°C) and T_t^{deep} (°C) are the changes in atmospheric and ocean temperature from pre-industrial levels at time t. β (W/m²°C) describes the efficiency at which heat moves between the atmosphere and deep ocean via the upper ocean, where C_{up} and C_{deep} (J/m²°C) are the heat capacity of the upper ocean and deep ocean, respectively. $\lambda = \frac{F_{2\times CO_2}}{ECS}$ (W/m²°C) is the feedback parameter. Feedbacks are processes that either exacerbate or diminish the warming or cooling, and one must take them into account when determining the impact of anthropogenic emissions on temperature.[5] $F_{2\times CO_2}$ is the change in radiative forcing that results from a doubling of CO_2, while the ECS is the change in temperature that results from a doubling of CO_2.

F_t (W/m²) is the increase in total radiative forcing from pre-industrial levels:

$$F_t = F_{2\times CO_2} \times \frac{ln\left(\frac{M_{A,t}}{M_{A,I}}\right)}{ln(2)} + F_{sol} \quad (6)$$

The radiative forcing depends on the concentration of carbon in the atmosphere through the ratio of current

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[5] An example would be cloud formation. A warmer atmosphere holds more water vapor, some of which turns into clouds. Cloud formation can exacerbate the initial warming by reflecting and re-emitting outgoing radiation back to the Earth's surface, but it can also create an albedo effect by reflecting incoming solar radiation back to space, suppressing the initial warming. The overall effect depends on the cloud's density, altitude, and the time of day.

Table 2 Temperature parameters

Parameter	Values
β	0.0880
$c_1 = \frac{\Delta t}{C_{up}}$	0.09798
$c_2 = \frac{\beta \Delta t}{C_{deep}}$	0.00025
$F_{2 \times CO2}$	3.70834
ECS	1.8, 3.1, 5.3

Source: van Kooten et al. (2021)

atmospheric CO_2 to the pre-industrial concentration ($M_{A,I}$ = 2189.634 Gt CO_2),[6] thus linking the carbon cycle to the temperature relationship. F_{sol} is exogenous forcing due to changes in solar irradiation, which we take as 0.05 W/m² (IPCC 2013, p.696). Table 2 lists the parameter values of the temperature equations, as well as $F_{2 \times CO2}$ and ECS.

Temperature Projections

We project the temperature deviation above pre-industrial levels for each RCP using the carbon-climate model. Using an ECS of 3.1 °C, our calibrated projections are very similar to the CMPIP5 ensemble average throughout most of the century for all RCPs (Fig. 3). The temperature is (relatively) high in the middle of the century for the RCP2.6 scenario, though the absolute deviation is only around 0.3 °C. The largest deviation occurs at the end of the century in the RCP8.5 scenario, with temperature underestimated by roughly 0.5 °C (10%). Calibrating the temperature projections to those from the CMIP5 ensemble allows our results to be compared to any research using CMIP5 projections. Standardizing the temperature projections also ensures that any extreme SCC values are not due to erroneous temperature projections. Last, it indicates that the simple carbon-climate model used here is capable of replicating projections of mean global temperature produced by the complex climate models employed by the IPCC.

As noted, we use four damage functions to estimate the SCC based on the EBM projections of CO_2 and temperature. Nordhaus (1991) initially proposed a damage function that most recent literature has built upon. In the DICE model, he assumes that damages can be well-approximated by a quadratic function of temperature:

$$1 - D(T) = \frac{1}{1 + 0.00236 T^2}, \tag{7}$$

where T is the temperature deviation in °C above pre-industrial levels and $D(T)$ is the proportion of economic output (GDP) lost due to climate change. Multiplying $D(T)$ by projected output will yield total damages. Under this function, damages equal 2.1% of global output at 3 °C of warming and 8.5% of output at 6 °C of warming (Nordhaus 2017).

Some have argued that the DICE damage function does not accurately represent damages at high levels of warming. Thus, Weitzman (2010) proposed the following damage function that approximates Nordhaus (DICE) damages at low-temperature increases, but has much greater damages at higher temperature increases:

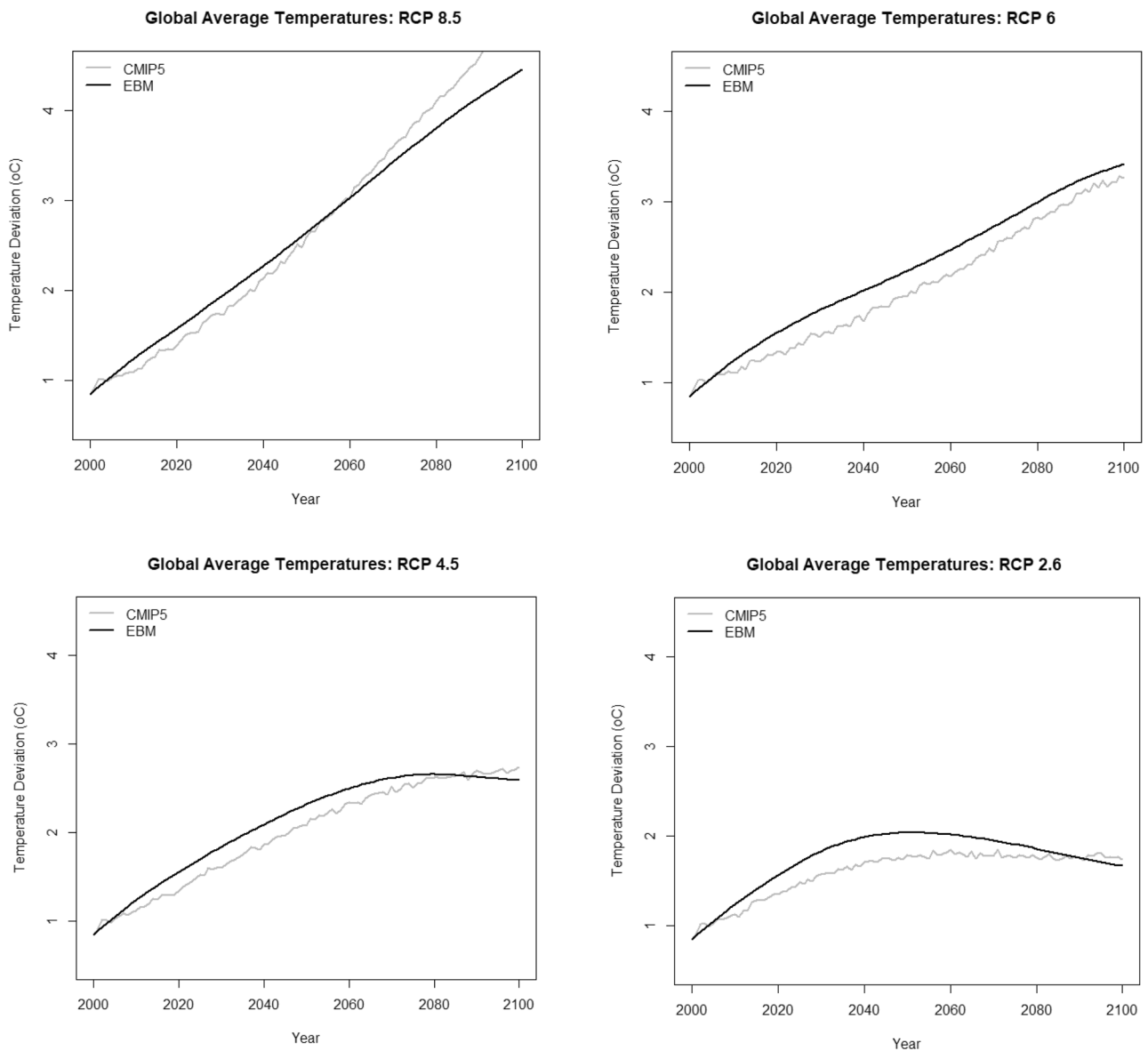$$1 - D(T) = \frac{1}{1 + \left(\frac{T}{20.2}\right)^2 + \left(\frac{T}{6.08}\right)^{6.76}} \tag{8}$$

The parameter values and exponents are chosen such that damages equal 50% of output at a temperature increase of 6 °C, and 99% of output at an increase of 12 °C (Ackerman and Stanton 2012). The rationale behind this assumption is based on the claim that warming as high as 12 °C could cause about half the world's population to experience conditions that human physiology cannot tolerate, resulting in death from heat stroke within a few hours (Ackerman and Stanton 2012; Sherwood and Huber 2010). A temperature increase of 12 °C represents the end of human life as we know it.

Figure 4 plots both Nordhaus and Weitzman damages. Because the Weitzman damage function is similar to that of Nordhaus for small temperature increases, the two equations should yield similar SCC estimates for lower emissions scenarios, such as RCP2.6 and RCP4.5. Conversely, the two damage functions will yield very different results for the high emission scenarios of RCP6.0 and RCP8.5, especially later in the century when temperature increases are highest.

The Golosov damage function uses the stock of atmospheric carbon, rather than temperature. While Nordhaus explicitly models the carbon-climate and climate-damages relationships, Golosov et al. (2014) formulate their damage function to capture both relationships in one step, assuming that the convexity of the climate-damages relationship exactly offsets the concavity of the carbon-climate relationship:

$$1 - D(S) = exp\left[-\gamma\left(S - \overline{S}\right)\right]. \tag{9}$$

S is the projected stock of carbon in the atmosphere measured in tonnes of carbon (tC) and $\overline{S}$ is the pre-industrial stock of carbon; $D(S)$ is the same as $D(T)$ in the previous equations—the proportion of future output lost due to climate change. The damage parameter, γ, is unknown until some future random date. All uncertainty is resolved at this

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[6] Mass of the atmosphere equals 5.148×10^{18} kg. Assuming a CO_2 concentration of 415 ppm, the mass of carbon in the atmosphere as a percent = $0.0415\% \times 44.0087$ g · CO_2 · mole⁻¹ / 28.971 g · mole⁻¹ = 0.06304% CO_2 by mass; multiply by the mass of the atmosphere to get the figure in the text.

Fig. 3 Projected temperatures: a comparison of the three-layered EBM outcomes vs. CMIP5 averages under the representative concentration pathways (RCPs)
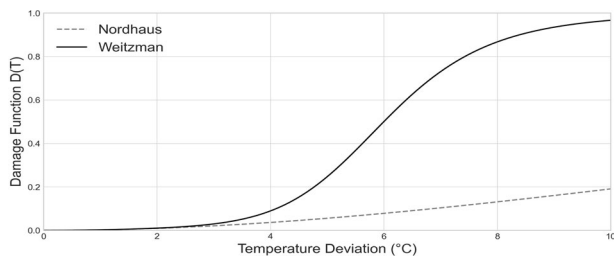
Fig. 4 A comparison of Nordhaus and Weitzman: damages across different temperatures

date and γ takes on a value of either $\gamma^L = 0.106 \times 10^{-5}$ or $\gamma^H = 2.046 \times 10^{-4}$ with some probability. The low and high values of γ are calibrated using the same assumptions as

Nordhaus (2008); namely, that damages equal 0.48% of output at 2.5 °C warming in a low-damage scenario and 30% of output at 6 °C warming in a high-damage scenario. The probability of the high-γ scenario occurring is assumed to be 0.068, resulting in an expected value of $\overline{\gamma} = 2.379 \times 10^{-5}$. They use $\overline{\gamma}$ in their calculation of damages, as does the current study. For the Golosov damage function, the SCC is roughly twice that found using Nordhaus damages.

Finally, the Burke damage function estimates the effect of temperature on economic growth using a panel study of 166 countries between 1960 and 2010. Notably, Burke et al. (2015) find that the optimal global temperature is about

13 °C (see Newell et al. 2021 for a critique). Since the average global temperature is currently above this level, any additional increase in temperature will cause economic damages. We follow their baseline model of the historical response function, which includes a linear and quadratic term for temperature:

$$h(T) = \beta_1 T + \beta_2 T^2 \qquad (10)$$

where T is temperature in °C and the coefficients, β_1 and β_2, are estimated as 0.0127 and −0.0005, respectively. The response function, $h(T)$, captures the impact of temperature on growth, and therefore describes economic growth under different climate scenarios.

Burke et al. (2015) estimate a global damage function by comparing economic growth in scenarios with and without climate change to see how much climate change reduces output:

$$1 - D(T) = exp\left\{ \left[h(T^+) - h(\overline{T}) \right] t \right\}, \qquad (11)$$

where T^+ is the projected temperature for any year after 2010 and T is the average temperature in 1980–2010. Since T^+ is the projected temperature rather than temperature deviation, it can be measured as the pre-industrial temperature plus the projected deviation. The variable t indicates the year, where 2010 is denoted by $t = 0$, 2011 by $t = 1$, et cetera.

In contrast to the previous damage functions, Burke damages are slightly concave but roughly linear in temperature rather than quadratic. This linearity results from the large distribution of temperatures across countries. For example, some countries are cold and possibly benefit economically from climate change, while others are warmer and experience negative economic impacts from climate change. This distribution means the average global impact of climate change varies little as emissions increase and temperatures warm, at least in the timeframe considered. The slight concavity of their damage function results from the finding that the marginal effect of climate on economic growth diminishes as emissions and temperatures increase. Therefore, higher emission scenarios will have a slightly lower SCC. The Burke damage function leads to an SCC that is usually 5–20 times higher than typical estimates from IAMs for temperature increases below 2 °C. At higher levels of warming, their SCC estimates are at least 2.5 times higher than IAM estimates—typically much higher.

Projections of Global Output

To find total damages, $D(T)$ or $D(S)$ must be multiplied in any given year by projected output for that year. Unless total output is endogenously determined in an IAM, it is necessary to employ exogenous projections of global
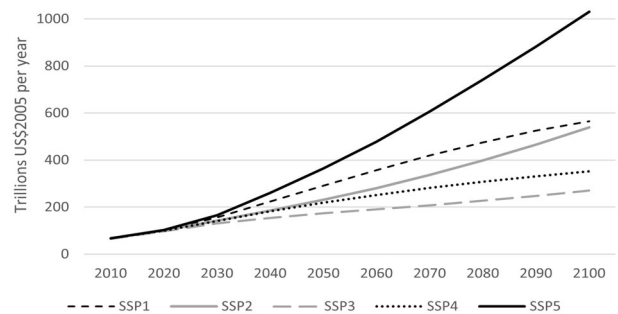
Fig. 5 Projected Annual Global Output under the Shared Socio-economic Pathways (SSPs)

output. We use projections under the SSPs.[7] The SSPs, or "storylines," offer five distinct socioeconomic scenarios with differing approaches to climate mitigation and adaptation—these are baseline scenarios (Riahi et al. 2017). Two storylines assume that future challenges to mitigation and adaptation are both low (SSP1) or both high (SSP3). SSP5 assumes high challenges to mitigation but low challenges to adaptation, while SSP4 assumes the opposite—namely, low challenges to mitigation but high challenges to adaptation. Finally, SSP2 assumes intermediate challenges to both mitigation and adaptation (Riahi et al. 2017). Figure 5 illustrates global output projections under the five SSP baseline pathways. All values are in 2005 U.S. dollars.

In addition to the baseline scenarios, the SSPs include mitigation scenarios to explore the implications of climate policy. The mitigation scenarios replicate the radiative forcing of the RCPs (as well as other forcing levels), allowing the socioeconomic outcomes of the SSPs to be easily linked to the emission pathways of the RCPs (Dellink et al. 2017). Therefore, we ensure that the assumptions on output, population, and other factors within the SSPs are consistent with the emission assumptions contained in the RCPs. In particular, we use SSP output projections to calculate total damages from emissions projected by the RCPs.

Due to the specific radiative forcing and emission levels of the RCPs, and the specific socioeconomic assumptions of the SSPs, some SSP storylines are unable to replicate all four radiative forcings. For example, the high emissions in RCP8.5 require very high economic and population growth, which only occur in SSP5; the other storylines have baseline forcing below this level (Riahi et al. 2017). Conversely, SSP3 is unable to achieve the low forcing of RCP2.6 due to high mitigation challenges and low income growth. This does not necessarily imply that RCP2.6 is infeasible if world outcomes are like those in SSP3; rather, it indicates only that certain low forcing levels cannot be produced within the modeling framework. These modeling issues do

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[7] SSP data are from https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10. We use the SSP marker scenarios.

Table 3 SSP mitigation scenarios and the representative concentration pathways[a]

	SSP1	SSP2	SSP3	SSP4	SSP5
RCP2.6	×	×		×	×
RCP4.5	×	×	×	×	×
RCP6.0		×	×	×	×
RCP8.5					×

[a]The marked spaces indicate that the given SSP is able to replicate the radiative forcing of the corresponding RCP

not exist in the real world. Therefore, the inability of SSP3 to achieve a radiating forcing of 2.6 W/m^2 in the simulations should be interpreted as a lowered probability of this transformation occurring in the real world (Riahi et al. 2017). Table 3 summarizes the RCP scenarios that each SSP storyline can replicate.

Social Cost of Carbon

We calculate the social cost of carbon in a given "base year" with the following equation:

$$SCC_{t=0} = \sum_{t=0}^{n} \left[\frac{DT_{M,t} - DT_t}{(1+r)^t} \right], \tag{12}$$

where DT_t refers to total damages in year t (referenced to the base year) for the standard RCP scenario, and $DT_{M,t}$ is total damages in year t for the RCP scenario in which an additional tCO_2 is added in the base year. This process is repeated every tenth year from 2020 to 2100, resulting in SCC estimates for nine different years. Because future damages must be discounted to the present, a discount rate (r) of 2.5% is chosen—we do not explore the implications of using different discount rates as this would lead to too many scenarios. We calculate the SCC for different combinations of the damage function, RCP scenario, SSP output and equilibrium climate sensitivity (ECS).

Results

Comparison across Damage Functions

To determine how the SCC varies with the chosen damage function, we consider a base case in which the ECS is set to 3.1 °C and output projections are from SSP5. We use SSP5 output projections simply because SSP5 is the only storyline able to replicate the forcing of all four RCPs. Since SSP5 has the highest output projections, it will result in the highest SCC estimates compared to the other SSP storylines. Model outputs begin in the year 2000, but we only report information for 2020 and beyond—this explains discrepancies in SCC across scenarios in 2020.

Figure 6 plots the SCC over time for each RCP and damage function with exact values of the SCC in 2020 and 2050 in Table 4. The SCC generally increases over time due to higher future concentrations of carbon in the atmosphere and greater global output (implying higher marginal damages). There is, however, a considerable amount of variation in the SCC across damage functions.

The SCC paths for the Nordhaus and Golosov damage functions change little across RCPs, indicating a low sensitivity to the chosen emission scenario. This can be explained by the offsetting of two opposing effects. When CO_2 concentrations are low, an additional emission has a larger effect on temperature (and therefore damages) than it would at high CO_2 concentrations (i.e., the carbon-climate relationship is concave). Contrariwise, the effect of temperature on damages is typically greater at higher CO_2 concentrations (i.e., the climate-damage relationship is typically convex).[8]

Nordhaus and Weitzman yield a very similar SCC time path for RCP2.6 because RCP2.6 has relatively low temperature increases (see Fig. 4). The Weitzman-determined SCC is, however, much higher in RCP8.5 than for the lower emission scenarios, indicating a greater sensitivity to the chosen RCP. This is because Weitzman damages are very sensitive to high temperatures.

Burke damages yield a much higher SCC than the other three damage functions for all but RCP 8.5, reaching a maximum of $12,500 per tCO_2 in 2100 for RCP2.6. The Burke SCC is lower for high emission scenarios because, unlike the other three damage functions, Burke damages are concave in temperature. This means that, after some point, higher temperatures will result in a lower SCC.

Sensitivity Analysis

Climate sensitivity and the social cost of carbon

To see how the SCC varies with the choice of ECS, we compare SCC estimates across RCPs under Nordhaus damages and SSP5 output projections (Fig. 7). Compared to an ECS of 3.1 °C, the SCC across all years decreases by more than half with an ECS of 1.8 °C. An ECS of 5.3 °C causes the SCC to more than double (compared to ECS = 3.1 °C) for each year under Nordhaus damages.

Tables 5 and 6 provide SCC estimates for ECS values of 1.8 and 5.3 °C for all four damage functions (cf. Table 4). Since Weitzman damages are quite sensitive to temperature, changes in the ECS tend to have a large impact on the Weitzman SCC. The Golosov SCC is unaffected by

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[8] The climate-damage relationship is convex for most damage functions; for the Burke damage function, damages are linear but exhibiting concavity at higher temperatures.
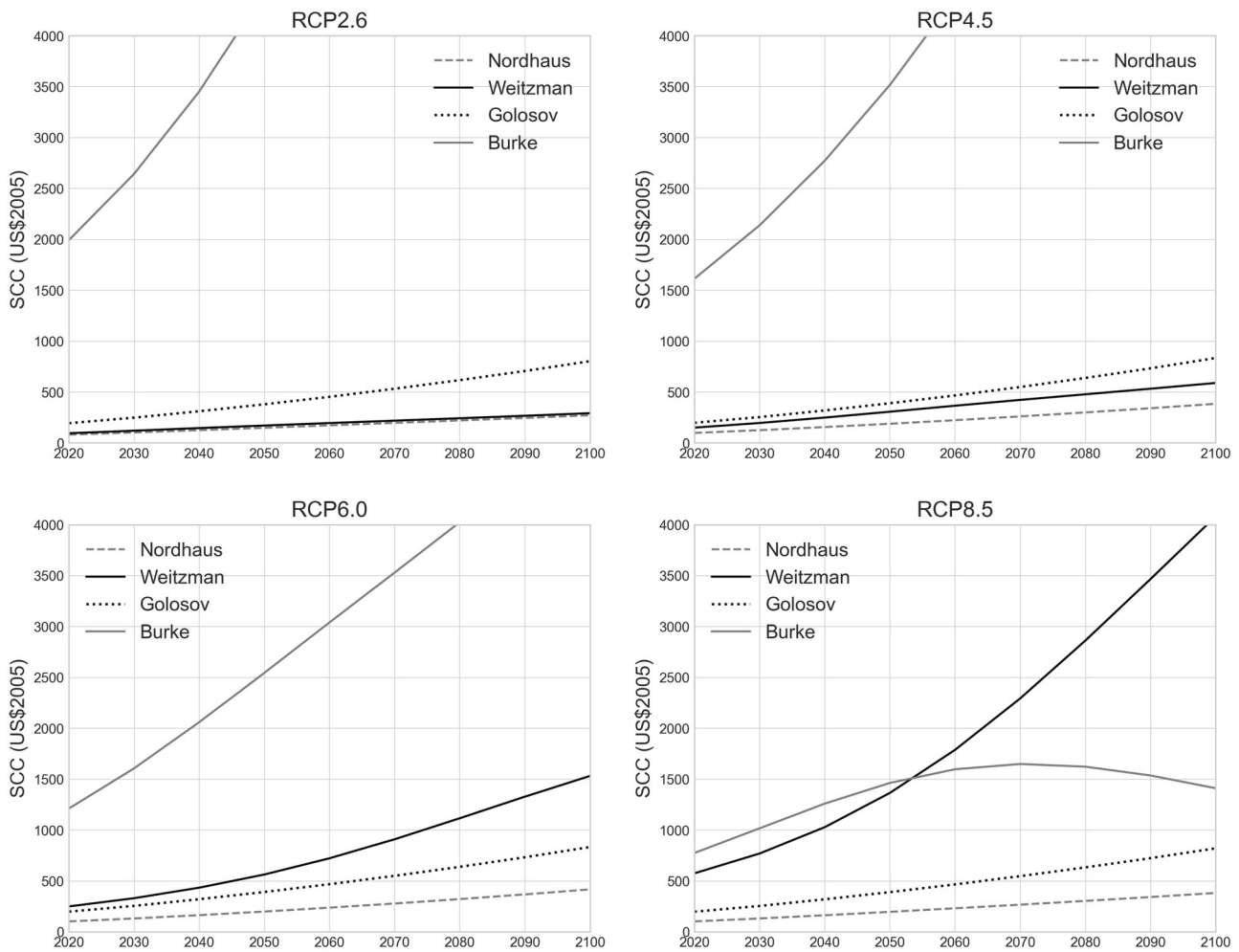
Fig. 6 Comparison of Social Cost of Carbon ($/tCO$_2$) across Damage Functions: SSP5, ECS 3.1 °C

Table 4 SCC ($/tCO$_2$) across damage functions for 2020 and 2050[a]

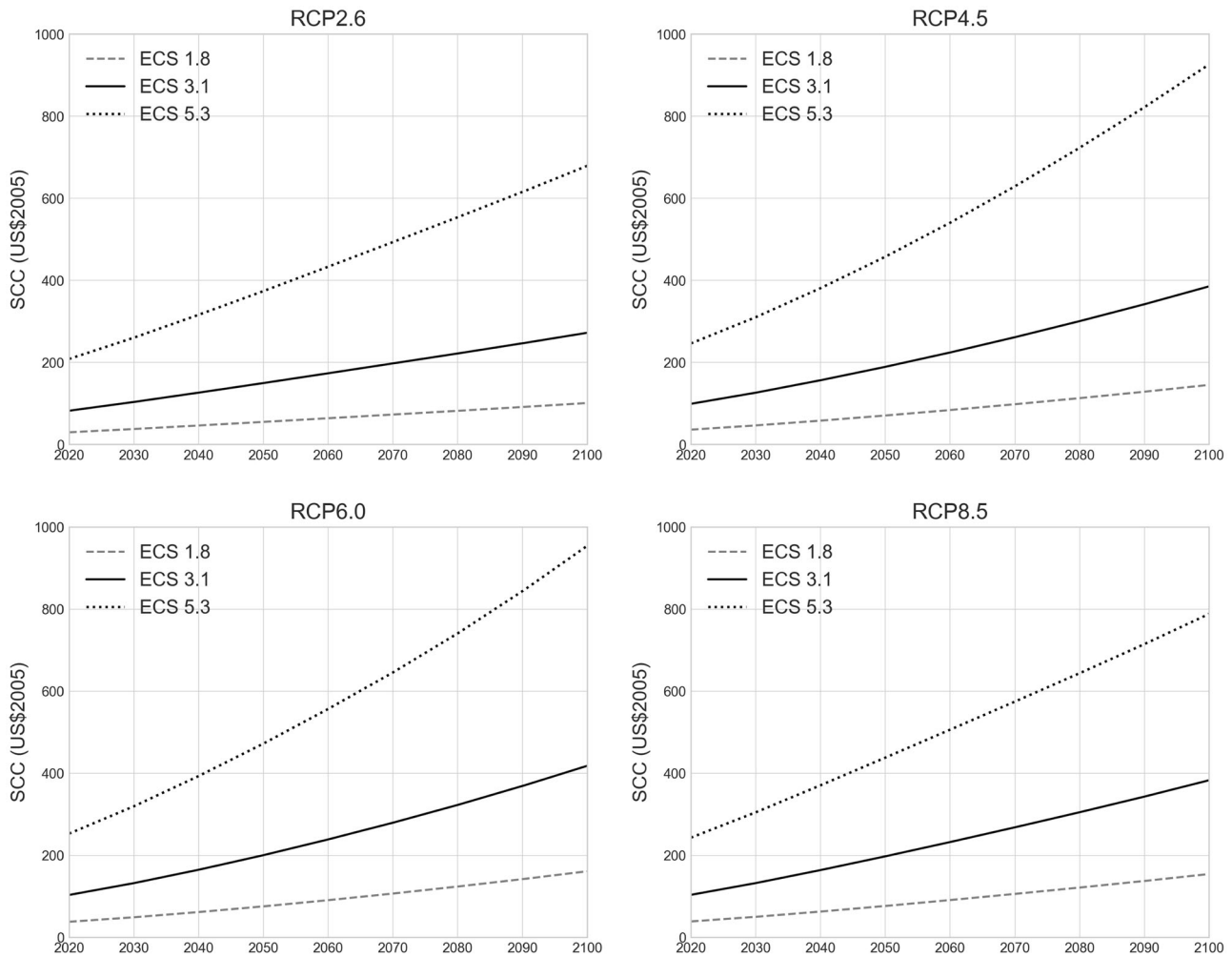| Pathway	Year	Nordhaus	Weitzman	Golosov	Burke
RCP2.6	2020	82.52	96.26	194.86	1994.13
	2050	149.85	171.93	380.41	4431.95
RCP4.5	2020	99.33	151.27	198.99	1615.14
	2050	189.39	307.75	390.85	3518.92
RCP6.0	2020	103.56	250.84	199.75	1212.84
	2050	200.45	564.42	392.62	2545.77
RCP8.5	2020	103.84	576.09	199.07	776.25
	2050	197.60	1366.32	391.38	1464.15

[a]Social cost of carbon calculated using an ECS of 3.1°C, a discount rate of 2.5% and SSP5 output projections. All values are US$2005

changes in ECS since the Golosov damage function uses the stock of carbon in the atmosphere rather than temperature. The Burke SCC is less sensitive to changes in the ECS relative to the Nordhaus and Weitzman SCCs.

Global output projections and the social cost of carbon

Because climate damages are measured as the percent loss in future output, the SCC is directly proportional to projections of global output. To see how the SCC increases as SSP output projections increase, SCC estimates are compared across different SSP storylines and RCPs under Nordhaus damages with an ECS of 3.1 °C (Fig. 8). Since not all SSP storylines can replicate the radiative forcing of each RCP, some plots do not include all five SSP. Notably, RCP8.5 is only achievable under SSP5, the highest of the output projections. For the other RCP scenarios, SSP5 leads to SCC estimates that are considerably higher than for the other SSP storylines.

Table 7 can be compared to Table 4 to see how the SCC for all damage functions is impacted by using SSP2 rather than SSP5 projections. We highlight SSP2 because it is the "middle-of-the-road" scenario that assumes current and historical trends will continue (Riahi et al. 2017). It has output projections that are in the middle of the other SSPs,

Fig. 7 Comparison of social cost of carbon ($/tCO$_2$) across ECS values: Nordhaus Damage Function, SSP5

Table 5 SCC ($/tCO$_2$) across Damage Functions for 2020 and 2050: ECS 1.8 °C[a]

Pathway	Year	Nordhaus	Weitzman	Golosov	Burke
RCP2.6	2020	29.97	31.46	194.86	1037.19
	2050	55.24	57.87	380.41	2357.93
RCP4.5	2020	36.39	39.34	198.99	945.59
	2050	70.82	77.22	390.85	2140.10
RCP6.0	2020	38.21	44.59	199.75	797.88
	2050	75.73	90.97	392.62	1789.84
RCP8.5	2020	39.04	69.56	199.07	534.87
	2050	76.70	149.80	391.38	1168.49

[a]Social cost of carbon calculated using an ECS of 3.1oC, a discount rate of 2.5% and SSP5 output projections. All values are US$2005

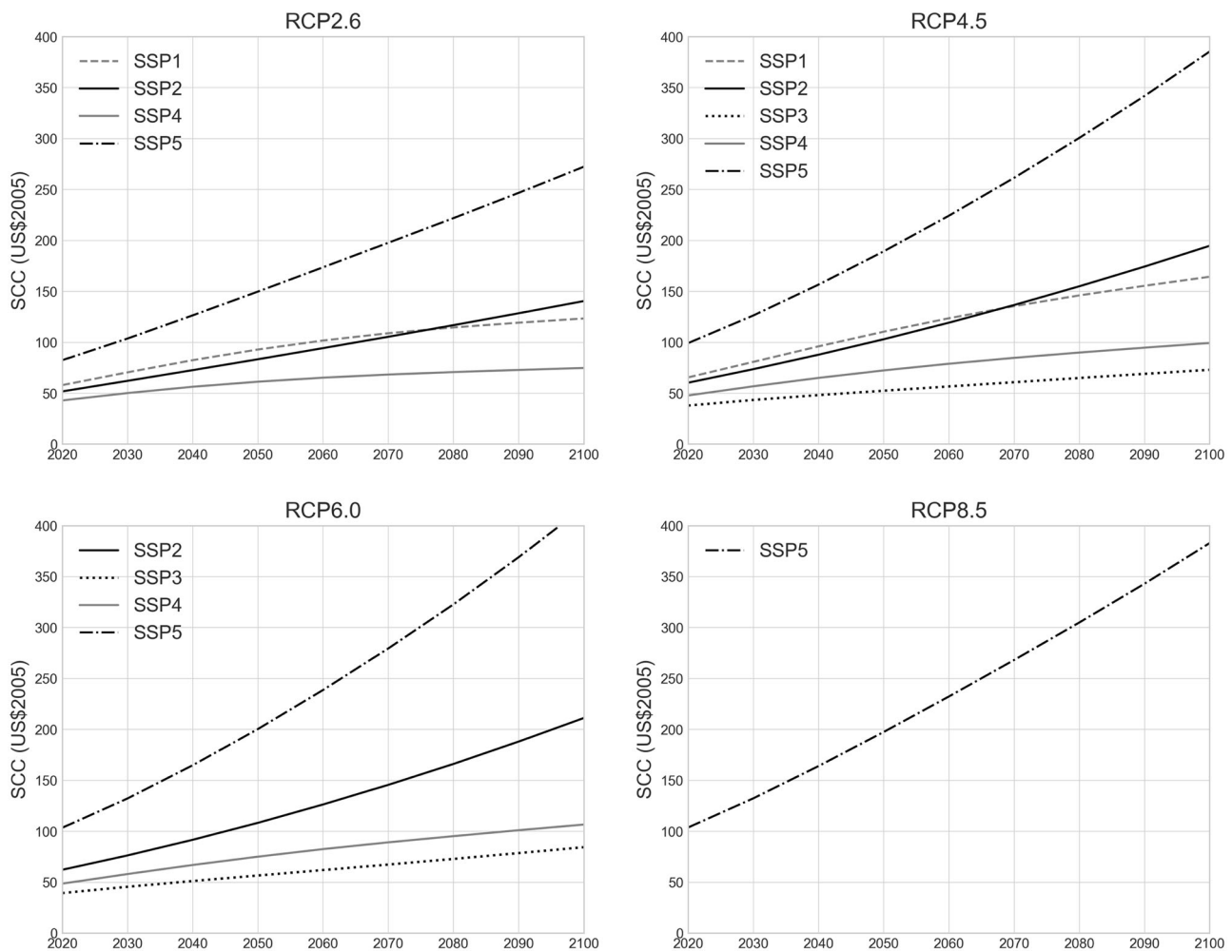**Table 6** SCC ($/tCO$_2$) across Damage Functions for 2020 and 2050: ECS 5.3 °C[a]

Pathway	Year	Nordhaus	Weitzman	Golosov	Burke
RCP2.6	2020	208.62	461.60	194.86	3324.55
	2050	373.94	785.67	380.41	7069.18
RCP4.5	2020	246.54	1283.64	198.99	2041.49
	2050	457.70	2751.61	390.85	3950.50
RCP6.0	2020	253.02	1999.65	199.75	1410.58
	2050	472.38	4582.69	392.62	2350.08
RCP8.5	2020	243.23	1492.67	199.07	969.83
	2050	438.14	3026.65	391.38	1244.21

[a]Social cost of carbon calculated using an ECS of 3.1oC, a discount rate of 2.5% and SSP5 output projections. All values are US$2005

providing a midpoint estimate of the SCC. Compared to SSP5, the SCC decreases by about half across all damage functions and emission scenarios under SSP2 output projections.

Policy Implications and Discussion

It is difficult to know which damage function is correct for a future climate (Warren et al. 2021). Limited data covering

Fig. 8 Comparison of social cost of carbon ($/tCO$_2$) across SSP output projections: Nordhaus damage function, ECS 3.1 °C

Table 7 SCC ($/tCO$_2$) across Damage Functions for 2020 and 2050 using SSP2[a]

Pathway	Year	Nordhaus	Weitzman	Golosov	Burke
RCP2.6	2020	51.86	60.86	125.65	1111.20
	2050	83.41	96.10	214.05	2361.09
RCP4.5	2020	60.42	90.48	126.91	909.66
	2050	103.07	168.00	216.94	1869.76
RCP6.0	2020	62.30	140.93	126.97	706.79
	2050	108.37	299.70	217.00	1376.44

[a]Social cost of carbon calculated using an ECS of 3.1oC, a discount rate of 2.5% and SSP5 output projections. All values are US$2005

the past century indicate that damages from climate change have so far been mild (Koonin 2021), with temperature increases limited to about 1 °C and within the range where at least three of the damage functions are roughly equivalent. If this remains true, then a damage function like that used by Nordhaus may be appropriate, while the Burke damage function appears too high. It may be possible, however, that higher increases in temperature cause greater damage. For instance, some are concerned that much of the economic damages from climate change will come from 'extreme events,' which can be thought of as "low-probability events with possibly massive economic consequences" (Auffhammer 2018, p. 47). If this is true, then the Weitzman or Burke damage functions may be appropriate in the future climate. Nonetheless, it is difficult to discern the causal effect that climate change has on extreme weather events, as well as to identify trends in the global and regional changes in extreme event occurrence (Seneviratne et al. 2012), making it impossible to know which specification is correct until better information is available.

In spite of uncertainty pertaining to the choice of damage function, it remains an essential component in estimating the SCC. The SCC, in turn, is needed to guide policy decisions. Since the SCC measures the marginal damages of CO$_2$ emissions, it also measures the marginal benefits of emissions reduction. Thus, the SCC should be compared to
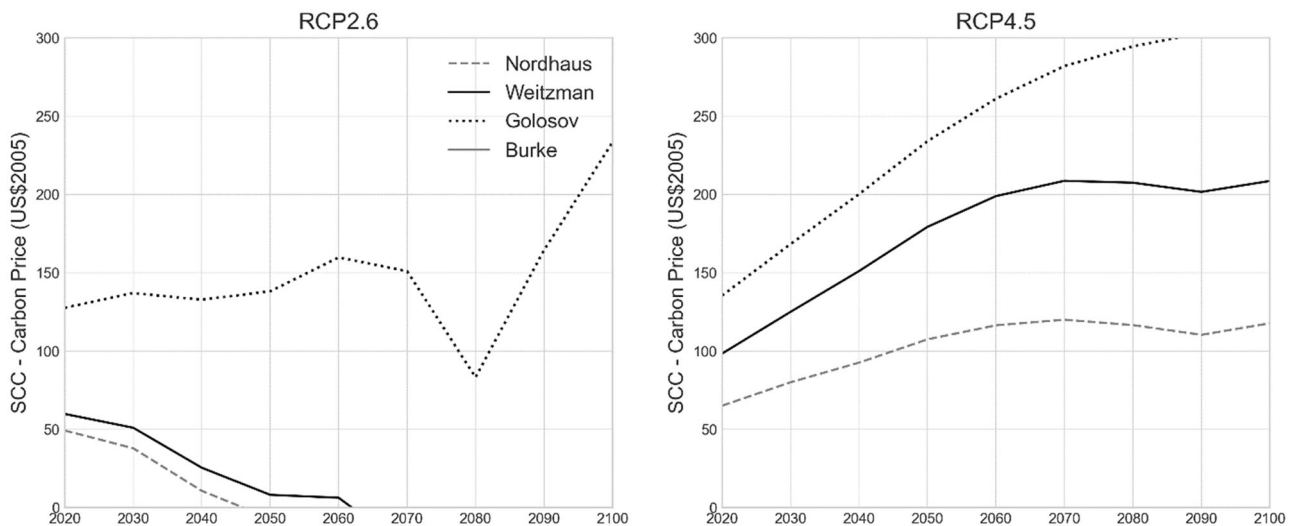
Fig. 9 Social cost of carbon minus carbon price: SSP1

the marginal cost of emissions reduction to determine the policy implications under the four damage functions. To ensure consistency between the SCC and the marginal cost of mitigation, we use cost estimates from the SSP mitigation scenarios, recalling that the SSPs were used to estimate our SCCs. Within the SSPs, the marginal cost of mitigation is measured as the carbon price. The carbon price of a given SSP mitigation scenario equals the tax that would need to be imposed to reduce the business-as-usual (BAU) emissions trajectory to the targeted RCP level. Each SSP storyline assumes somewhat different BAU trajectories as well as different challenges to mitigation. Thus, each SSP will have a different carbon price for a given RCP emissions target. For example, the carbon price in 2050 for RCP2.6 is about $100 under SSP1, which constitutes a low challenge for mitigation, and almost $260 under SSP5, which makes mitigation more difficult and leads to higher BAU emissions.

We compare the SCC estimates obtained in this study to the carbon price (abatement cost) estimates from the SSP mitigation scenarios. If the SCC for a given SSP scenario is greater than the corresponding carbon price, additional mitigation should occur, i.e., emissions should be reduced. For example, if the estimated SCC is $200 and the carbon price is $100 for a given SSP, emissions can be reduced by increasing the carbon price (e.g., via an increased carbon tax or reduced number of emission permits allowed). Contrarily, if the carbon price is greater than the SCC, less mitigation should occur. Ultimately, the optimal emissions trajectory is where the carbon price equals marginal damages as measured by the SCC.

We only consider an ECS of 3.1 °C; note that other ECS values will likely have different implications. Figures 9–13 plot the estimates of SCC minus carbon price—marginal benefit of mitigation minus the marginal abatement cost—

Table 8 Carbon Prices and SCC ($/tCO$_2$) in 2050 for Various RCP and SSP Scenarios[a, b]

Pathway	Carbon Price	Nordhaus	Weitzman	Golosov	Burke
RCP 2.6					
SSP4	185.47	61.38	71.64	159.64	**1482.36**
SSP1	99.97	92.98	**108.13**	**238.10**	**2321.74**
SSP2	84.71	83.41	**96.10**	**214.05**	**2361.09**
SSP5	258.40	149.85	171.93	**380.41**	**4431.95**
RCP 4.5					
SSP3	64.58	52.53	**86.60**	**116.54**	**877.91**
SSP4	53.98	**72.47**	**119.71**	**158.90**	**1208.02**
SSP1	3.04	**110.47**	**182.30**	**237.00**	**1876.08**
SSP2	12.32	**103.07**	**168.00**	**216.94**	**1869.76**
SSP5	92.38	**189.39**	**307.75**	**390.85**	**3518.92**
RCP 6.0					
SSP3	28.59	**56.64**	**147.58**	**120.18**	**720.25**
SSP4	5.61	**75.15**	**195.03**	**158.38**	**956.31**
SSP2	2.35	**108.37**	**299.70**	**217.00**	**1376.44**
SSP5	36.28	**200.45**	**564.42**	**392.62**	**2545.77**

[a]Social cost of carbon calculated using an ECS of 3.1oC, a discount rate of 2.5% and SSP5 output projections. All values are US$2005

[b]Bold values indicate that SCC exceeds the carbon price, indicating that further mitigation is beneficial

for each damage function and each RCP scenario for a given SSP storyline for the years 2020–2100. Additional emission reduction is desirable if the difference is positive. In the figures, the Burke SCC greatly exceeds the carbon price by more than $400 per tCO$_2$ (see also Table 8 below) so it is indicated in the legend but not plotted in the figures, thereby enabling us to better distinguish the separate
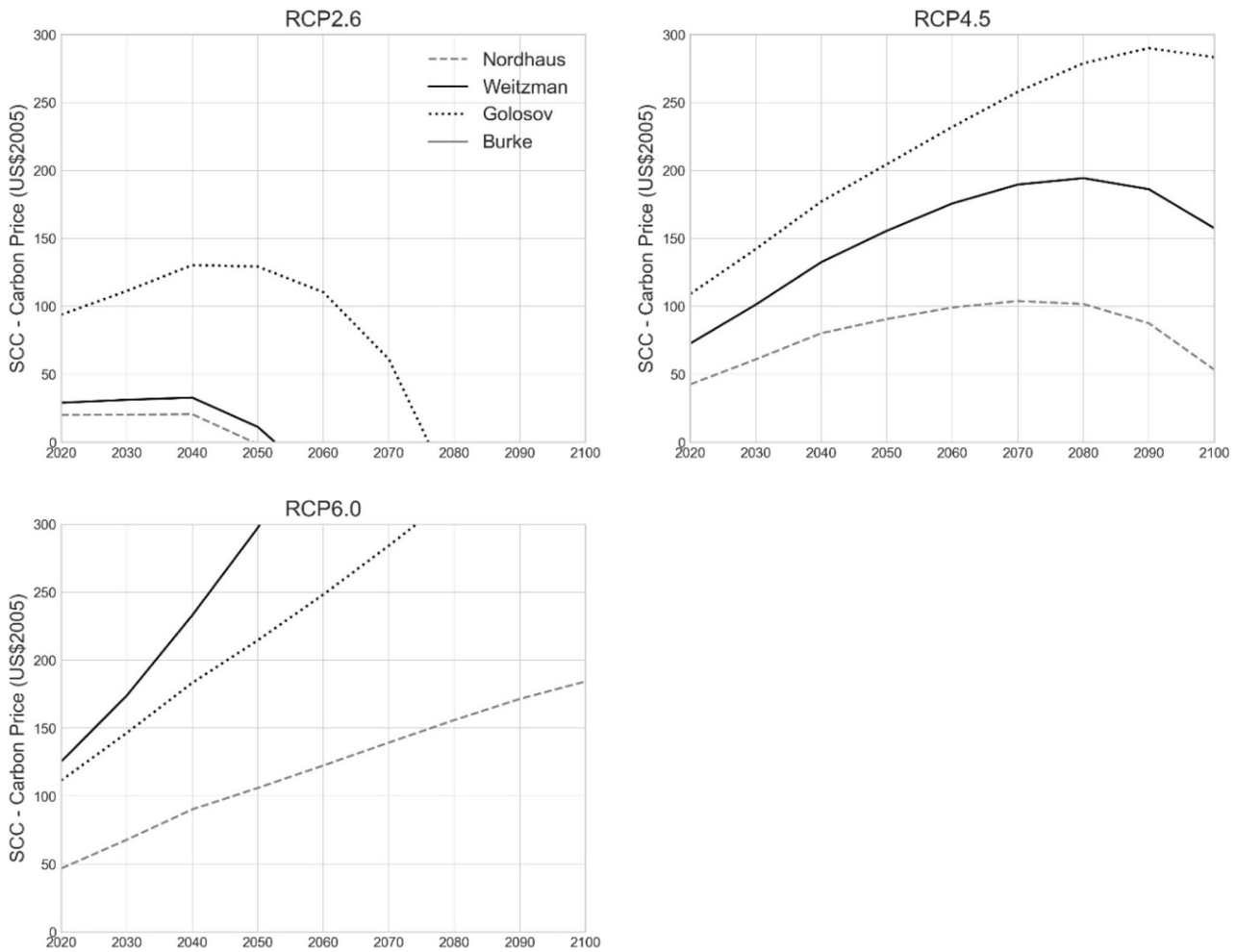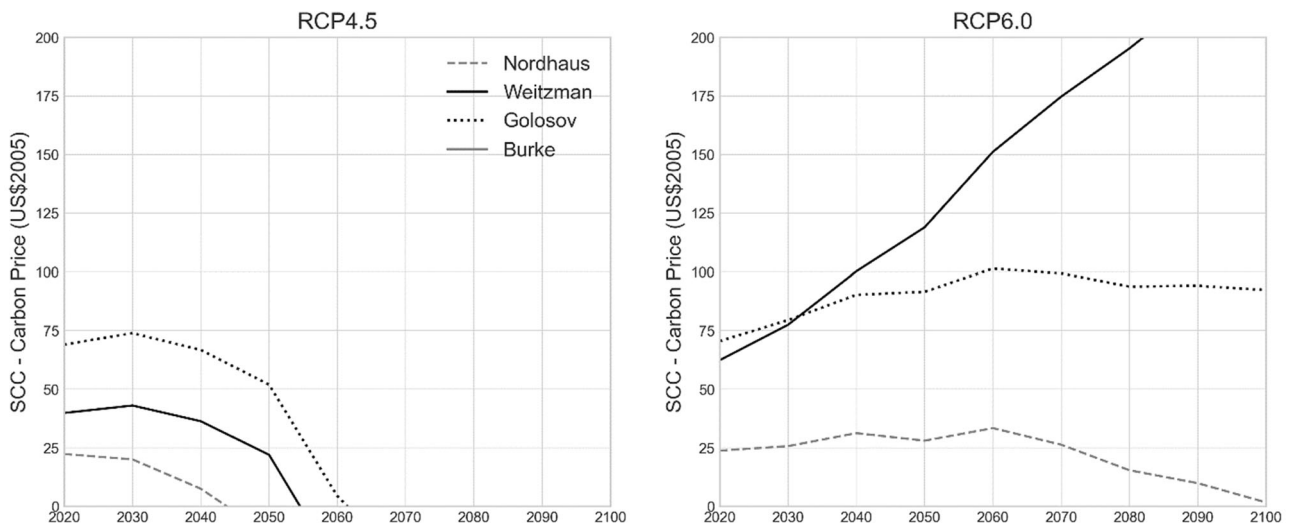
Fig. 10 Social cost of carbon minus carbon price: SSP2

damage functions. What it does imply is that it will always be beneficial to mitigate under the Burke damage function.

SSP1 has moderate-to-high global output projections, indicating a moderate-to-high SCC. It also assumes that both challenges to mitigation and baseline emissions will be low, meaning that the carbon price will be relatively low. Together these assumptions indicate that emissions reduction will likely be desirable in this scenario. Figure 9 plots the SCC minus carbon price estimates for each RCP under SSP1, which is only able to replicate RCP2.6 and RCP4.5. Under RCP2.6, additional mitigation is desirable for all damage functions until about 2045, after which the carbon price is greater than the Nordhaus SCC. Shortly thereafter, around 2060, mitigation is no longer desirable under Weitzman damages. The Golosov and Burke damage functions imply that mitigation to get below RCP2.6 emissions would indeed be desirable for the entire period, since the SCC is always greater than the carbon price. For RCP4.5, additional mitigation is always optimal, meaning that reducing emissions below RCP4.5 is desirable no matter the damage function.

SSP2 is the "middle-of-the-road" scenario, where output projections and challenges to mitigation are both intermediate. This implies that the SCC and carbon price estimates will also be intermediate, relative to other SSPs. The plots for SSP2, which can reproduce RCPs 2.6, 4.5, and 6.0, are provided in Fig. 10. For RCP2.6, mitigation under all damage functions is optimal until about 2050, after which the carbon price is greater than both the Nordhaus and Weitzman SCC. In ~2075, the carbon price surpasses the Golosov SCC as well, indicating that the RCP2.6 pathway is too low under these three damage functions. For RCP4.5 and RCP6.0, additional mitigation is desirable for all damage functions.

SSP3 assumes that challenges to mitigation will be high, implying a high carbon price. It also assumes that global output will be low, indicating a low SCC. Together, these assumptions suggest that only a small amount of abatement should occur. The difference between the SCC and the carbon price under SSP3 assumptions is plotted in Fig. 11 for RCP4.5 and RCP6.0. For RCP4.5, the carbon price is

Fig. 11 Social cost of carbon minus carbon Price: SSP3

greater than the SCC for the Nordhaus, Weitzman and Golosov damage functions after 2060. Thus, mitigation beyond RCP4.5 is only optimal for the entire period under the Burke damage function. Mitigation beyond RCP6.0 is likely desirable for all four damage functions, with the carbon price below the SCC throughout the century.

SSP4 assumes low challenges to mitigation and has low-to-moderate output projections—both the carbon price and SCC will be relatively low. Figure 12 plots the SCC minus carbon price estimates for SSP4 for RCPs 2.6, 4.5, and 6.0. The carbon price increases quickly for RCP2.6; after about 2045, additional mitigation is optimal only under Burke damages. After about 2070, mitigation beyond RCP4.5 is desirable only under Golosov and Burke damages. For RCP6.0, the carbon price is less than the SCC for all damage functions, meaning that additional emissions reduction will likely be economically desirable.

Last, SSP5 assumes that both challenges to mitigation and baseline emissions will be high, implying a high carbon price. Additionally, it assumes high global output, indicating a high SCC. Figure 13 plots the SCC–carbon price difference for SSP5 for all four RCP scenarios. The carbon price for RCP2.6 surpasses the Nordhaus, Weitzman and Golosov SCC just before 2060, with additional emission reduction desirable only for the Burke damage function. For RCP4.5, emission reduction for all damage functions is desirable for most years, except after 2090, when the carbon price surpasses the Nordhaus SCC. For RCP6.0 and RCP8.5, emission reduction is always desirable. The carbon price for RCP8.5 is zero since no carbon tax (or any other climate policy) is needed to reach RCP8.5 emission levels under the SSP5 scenario.

These five figures show how the difference between SCC and the carbon price changes over time for alternative SSP

mitigation scenarios, where each mitigation scenario targets a specific RCP level. It is evident that reducing emissions below RCP6.0 emissions will likely be desirable in all cases. Emission reduction beyond RCP4.5 is desirable in most cases, while reduction beyond RCP2.6 is often not desirable over the entire period, depending on the damage function and SSP scenario.

To get a better idea of how optimal policy varies across RCP scenarios, we provide the carbon price and SCC estimates for RCP2.6, RCP4.5 and RCP6.0 (Table 8). We do not include information for RCP8.5 since this pathway is only plausible as a BAU scenario. Since no mitigation is required to reach RCP8.5 emissions, the carbon price is zero so reducing emissions by any amount will always be marginally beneficial if done using a revenue-neutral carbon tax. Values for 2050 are compared because many long-term emission targets, such as those under the Paris Agreement, require dramatic mitigation by this year, with many countries committed to be carbon neutral by that date. The carbon price and SCC values indicate the economic desirability and feasibility of achieving these targets. Where the SCC estimates are greater than the carbon price, they are underlined and bolded, indicating further mitigation is beneficial; non-bold values indicate that mitigation should be reduced and emissions allowed to increase. However, recall that the carbon prices (marginal abatement costs) were determined by integrated assessment models used to develop the SSPs and RCPs. If these values happened to be biased downward, optimal abatement policies would be less restrictive that those suggested by our results, and vice versa.

Roughly half of the 16 combinations indicate that mitigation to get below RCP2.6 emissions would be socially desirable in 2050. Therefore, targets under the Paris
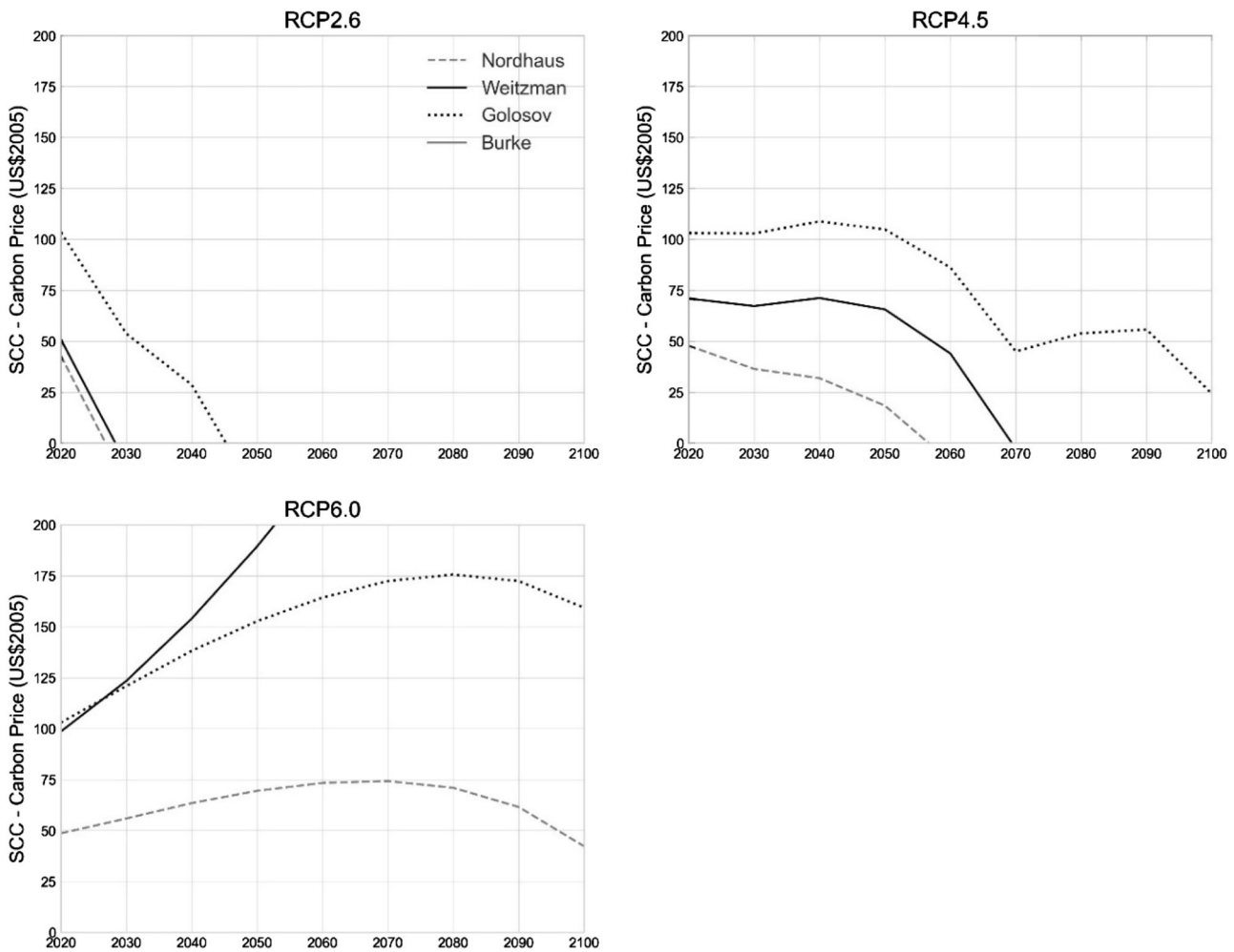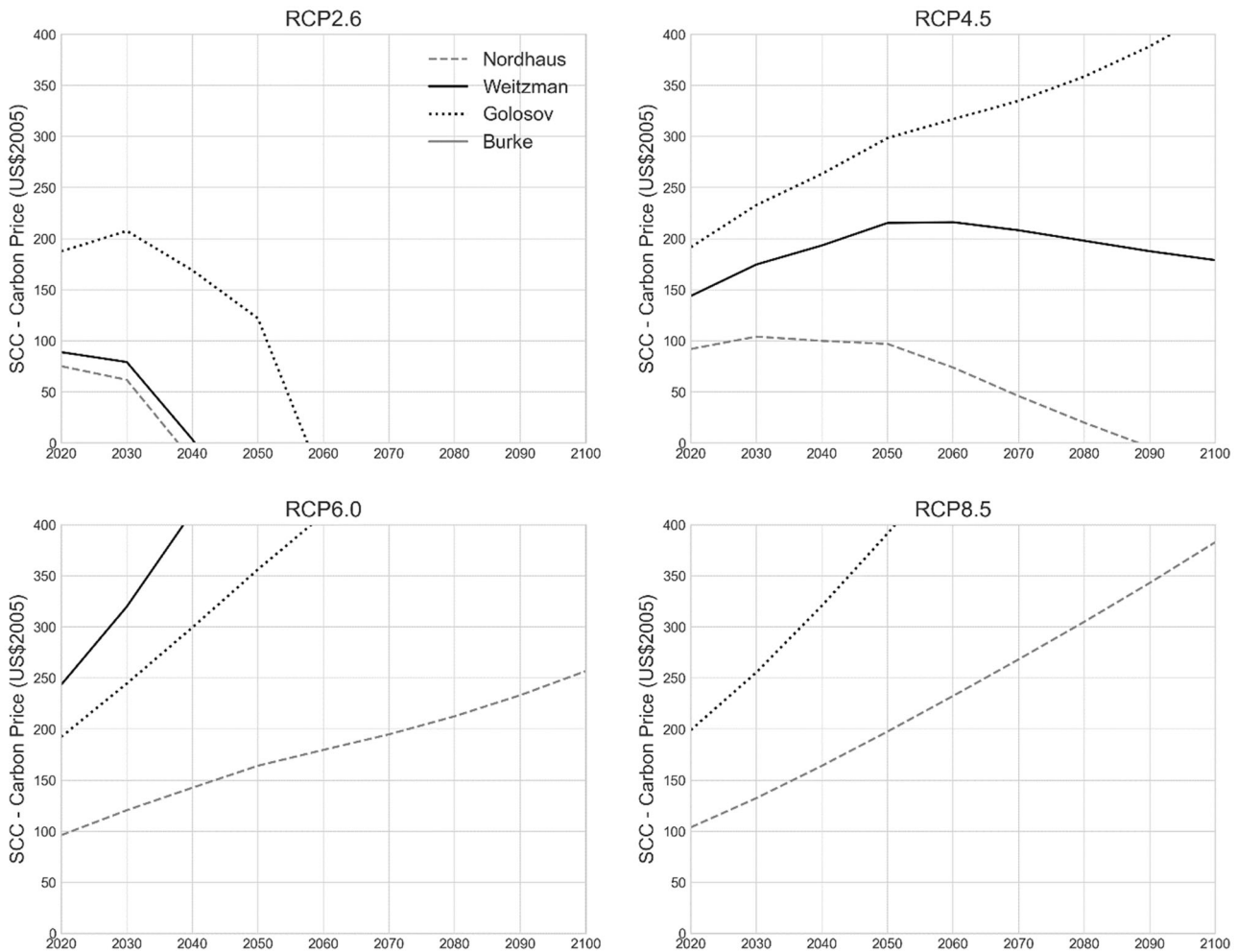
Fig. 12 Social cost of carbon minus carbon price: SSP4

Agreement may or may not be economically feasible, depending on how damages and costs manifest over the coming decades. There is only one instance under RCP 4.5 in which SCC falls below the carbon price (Nordhaus damages under SSP3). As such, additional abatement will likely be desirable under RCP4.5 in 2050. All SCC estimates are greater than the carbon price for RCP6.0, indicating that emissions reduction to get below RCP6.0 emissions in 2050 will very likely be optimal. This is partly due to the low carbon price estimates for RCP6.0. Most SSP storylines have baseline forcing close to 6.0 W/m^2, meaning only a small amount of mitigation (low carbon tax) is needed to reduce emissions to this level.

Overall, this comparison suggests that, with an ECS of 3.1 °C and a discount rate of 2.5%, additional emissions reduction will likely be optimal under RCP6.0 and RCP8.5 regardless of the damage function that is considered—at least until the end of the century, and that any policy that aims to reduce emissions beyond RCP6.0 will be desirable, no matter the chosen damage function or SSP scenario. For

the lower emission pathways, optimality depends on the damage function and SSP scenario. For RCP2.6, the carbon price for all SSP scenarios surpasses the Nordhaus and Weitzman SCC by 2060 at the latest. Thus, policy to target this pathway may be optimal in initial years, but the required carbon price becomes greater than the marginal benefits (SCC) in the long run. In other words, for this low-emission pathway, the marginal costs of mitigating climate change are projected to outweigh the marginal benefits roughly halfway through the century, and policy that targets a higher emissions pathway may be preferable. However, the Burke SCC indicates that abatement beyond RCP2.6 emissions is indeed optimal, while the Golosov SCC indicates that abatement is desirable in some cases, depending on the SSP. Emission reduction beyond RCP4.5 is desirable for all damage functions in two SSP scenarios. For the other SSPs, the carbon price surpasses at least one of the SCC time paths. To determine the optimality of RCP2.6 and RCP4.5, uncertainty about the damage function and SSP storyline needs to be resolved. Alternatively, policy could

Fig. 13 Social Cost of Carbon minus Carbon Price: SSP5

target an RCP2.6 outcome in the first half of the century, then ease off again to target RCP4.5 emissions thereafter.

It is also important to note that, like the SCC estimates presented here, marginal cost of abatement estimates are also uncertain. The carbon prices we used are from the SSP marker scenarios, which are meant to represent the broader scope of each SSP (Riahi et al. 2017). Some models used for determining SSP outcomes project different abatement costs. Nonetheless, the values used here offer an approximation of whether emissions reduction will be desirable under certain conditions.

Conclusions

Social cost of carbon estimates are needed to make decisions on strategies for mitigating climate change as they provide an indication of the potential economic benefits of mitigation. Unfortunately, there is significant uncertainty in estimating the economic damages from climate change due

to a lack of empirical evidence and economic theory. This makes it difficult to determine the proper form of the damage function. To see how the chosen damage function impacts the SCC, we used RCP emission scenarios and a simple carbon-climate model that results in temperature projections similar to the CMIP5 ensemble average. Using the temperature and carbon projections, we found that estimates of the SCC differed greatly and depended on the particular damage functions. Results from the Weitzman (2010) and Burke et al. (2015) damage functions are sensitive to emissions scenarios, while those of Nordhaus (2017) and Golosov et al. (2014) were much less sensitive to emissions scenarios. Further, values of the SCC turned out to be quite sensitive to the equilibrium climate sensitivity and level of projected global output.

It is difficult to know what the economic damages from climate change will be until these temperature changes actually occur. At the same time, the economic damages are not due to temperature alone, but other factors such as changes in precipitation and drought or the occurrence of

other extreme events, which are related to changes in temperature (IPCC 2021). However, the results of this paper suggest that efforts to reduce emissions below those of RCP6.0 throughout the century are likely to be socially desirable, no matter the damage function. Reducing emissions below RCP4.5 and RCP2.6 could still be economically viable in the first half of the century (e.g., to meet Paris agreement targets), with the long-term benefit dependent on the damage function. To determine the feasibility of targeting a lower emissions pathway up to 2100, such as RCP2.6 or RCP4.5, better information on the damage function is needed. Further research should attempt to better-quantify the damages from climate change so that the SCC can be estimated with greater precision. Additionally, further research should attempt to better quantify the challenges to mitigation, thereby providing more accurate estimates of the carbon price. This would provide a better indication of the feasibility of achieving a given emissions target.

Author Contributions ARR: contributed to writing (original draft preparation), formal analysis, and data curation. GCvK: conceptualized research, supervision, funding acquisition, and contributed to formal analysis and writing (review and editing). JGI and MEE: contributed to data curation, formal analysis and writing (review and editing).

Compliance with Ethical Standards

Conflict of interest The authors declare no competing interests.

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