

van der Ploeg, Rick; Emmerling, Johannes; Groom, Ben

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The Social Cost of Carbon with Intragenerational Inequality under Economic Uncertainty

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Frederick van der Ploeg, Johannes Emmerling, Ben Groom

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Poschingerstr. 5, 81679 Munich, Germany

Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de

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Abstract

A formula is derived for the social cost of carbon (SCC) that takes account of intragenerational income inequality and its evolution with economic growth. The social discount rate (SDR) should be adjusted to account for intragenerational and intergenerational inequality aversion and for risk aversion. If growth increases (reduces) intra-generational inequality, the SDR is lower (higher) and the SCC higher (lower) than along an inequality-neutral growth path, especially if intra-generational and intergenerational inequality aversion are higher. The same qualitative result is shown for two welfare specifications, one with a representative agent with equally distributed equivalent (EDE) income and the other considers individuals separately across the income distribution. The latter specification causes an additional impact of income inequality on the SDR and SCC because individuals are compared both within and between time periods. Our preferred EDE calibration to a scenario in which global intragenerational inequality declines over time, leads to a SCC in 2020 of \$70/tCO₂ compared to a value of \$85/tCO₂ without the effect of inequality.

JEL-Codes: C610, D310, D620, D810, G120, H230, Q540.

Keywords: social discount rate, social cost of carbon, intra- and intergenerational inequality aversion, risk aversion, inequality, growth, uncertainty.

Frederick van der Ploeg
Department of Economics
University of Oxford
United Kingdom - Oxford OX1 3UQ
rick.vanderploeg@economics.ox.ac.uk

Johannes Emmerling
RFF-CMCC European Institute on Economics
and the Environment (EIEE), Centro Euro-
Mediterraneo sui Cambiamenti Climatici
Italy - 20144 Milan
johannes.emmerling@eiee.org

Ben Groom
Dragon Capital Chair of Biodiversity
Economics, LEEP Institute, Department of
Economics
University of Exeter / United Kingdom
B.D.Groom@exeter.ac.uk

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1 Introduction

The social discount rate (SDR) has important implications for the economic appraisal of public investment projects and regulatory change. The sensitivity of the social cost of carbon (SCC) to the SDR implies that the implications of discounting for appraisal of climate policy are particularly important. This has been reflected in policy circles with recent calls for a refocusing of climate policy on more scientific assessments of the SCC, and clearer guidance on the appropriate SDR (Aldy et al., 2021). Current estimates of the SCC used in policy circles ignore many factors that are relevant for welfare in the context of climate change (Wagner et al., 2021). Perhaps chief among these omissions is the issue of intragenerational, rather than intergenerational inequality. While there are general calls for accounting for the distributional effects of environmental policy in appraisal (e.g. Drupp et al., 2021), evidence from Integrated Assessment Models shows that the potential welfare implications of intragenerational inequality aversion might be an important determinant of the SCC (Dennig et al., 2015; Kornek et al., 2021). Furthermore, in the United States, Executive Order 13990 specifically requires inequality to be considered in the assessment of the economic impacts of air pollutants including CO₂ (IAWG, 2021). Taken together, there is a clear need to provide methodological guidance and transparent estimates of the SCC that take into account inequality and inequality aversion, both inter- and intragenerationally, and better reflect the welfare effects of climate change. Progress here could inform policy processes like the recent Biden administration’s review of climate policy and the SCC.

In this paper we address this important policy issue by adjusting the Keynes-Ramsey rule for the SDR to take account of both intra- and intergenerational inequality aversion, correcting for the fact that the standard representative-agent approach ignores aversion to intragenerational income inequalities (Dasgupta, 2008; Gollier, 2015; Emmerling et al., 2017; Fleurbaey et al., 2018). Our aim is to provide the simplest possible framework for evaluating the SDR and the SCC accounting for inequality both within and across generations, as well as for uncertainty about the future rate of economic growth. Our approach distinguishes measures of intragenerational and intergenerational inequality aversion separately, and by using recursive preferences (Kreps and Porteus, 1978; Epstein and Zin, 1989; Duffie and Epstein, 1992a,b) also disentangles measures of relative risk aversion and aversion to intertemporal fluctuations.

We model the dynamics of the intragenerational income distribution with a lognormal income distribution (e.g., Pinkovskiy and Sala-i Martin, 2009). This allows the analysis

of distributions that become over time more unequal, less unequal, or stay the same as the economy grows to be captured by a single parameter, the coefficient of variation. To illustrate the relative importance of preferences over inter- and intragenerational inequality, and uncertainty, on the SCC we calibrate a simple climate-economy model with global warming damages as fraction of world economic activity roughly linear in temperature (Burke et al., 2015; Kalkuhl and Wenz, 2020), temperature driven by cumulative emissions (e.g., Matthews et al., 2009; van der Ploeg, 2018; Dietz and Venmans, 2019), and global mean consumption growth given by a geometric Brownian motion with risks of rare macroeconomic disasters (Barro, 2009). Coupled with inequality in consumption levels across agents at a particular point of time represented by a lognormal distribution, we show how the SDR and the optimal SCC depend not only on uncertainty about the future rate of growth of the economy, but also on intra- and intergenerational inequality, and the three preference measures regarding intra- and intergenerational inequality aversion and risk aversion. The inclusion of the two types of inequality, appropriately calibrated preferences, uncertainty and catastrophic risk addresses a number of additional omissions in the typical calculation of the SCC highlighted by Wagner et al. (2021).

Section 2 defines the equally-distributed-equivalent (EDE) level of consumption as in Atkinson (1970) and gives expressions for the level and growth of mean and per-capita consumption and of EDE consumption. Sections 3 and 4 discuss intra- and intergenerational inequality aversion, and derive the inequality-adjusted SDR. Section 5 gives the optimal SCC adjusted for intra- and intergenerational inequality aversion. Section 6 allows for growth uncertainty, the risk of rare macroeconomics disasters, and risk aversion. Section 7 calibrates our model and section 8 quantifies the SDR and SCC for various preferences regarding intra- and intergenerational inequality aversion and risk aversion, and for several SSP scenarios corresponding to the Shared Socioeconomic Proposals (SSPs) over the 21st century (SSP2), see Riahi et al. (2017). Section 8 summarises our results and suggests directions for further research.

2 Equally-distributed equivalent consumption

Following Emmerling et al. (2017), consider at time t an economy with a continuum of agents of type θ with cumulative probability density function $F_t(\theta)$ and assume that this density function is the same for all points of time. At a particular moment of time t , the instantaneous felicity function of an agent of type θ is $U(c_t(\theta))$, where $c_t(\theta)$ de-

notes consumption of this agent at time t . We assume that the felicity function has a *constant* elasticity of marginal utility with respect to consumption, so the felicity function is $U(c_t(\theta)) = (c_t(\theta)^{\eta-1} - 1)/(1 - \eta)$ if $\eta \neq 1$ and $U(c_t(\theta)) = \ln c_t(\theta)$ if $\eta = 1$. The elasticity $\eta = -c_t U''(c_t(\theta))/U'(c_t(\theta)) > 0$ is the coefficient of relative intragenerational inequality aversion. This coefficient is the same for all agents and constant over time. The equally-distributed-equivalent (EDE) level of consumption at a given point in time t is that constant level of consumption that gives the same felicity as the actual distribution of consumption levels (Atkinson, 1970). The level of EDE consumption can be written as $c_t^{EDE} = U^{-1}(\int_{\theta} U(c_t(\theta)) dF(\theta))$. The Atkinson inequality index is defined as $I_t(\eta) \equiv (c_t^{mean} - c_t^{EDE})/c_t^{mean}$ and satisfies the axioms of anonymity, aversion to mean-preserving spreads, and aversion to population and income scale. EDE consumption can be viewed as the sure income an agent would be indifferent to compared with the prospect of obtaining a random draw from the income distribution behind the “veil of ignorance”.

We assume that consumption of agents at time t is lognormally distributed with mean μ_t and standard deviation σ_t , so $\ln c_t(\theta) \sim N(\mu_t, \sigma_t^2)$. This gives EDE consumption

$$c_t^{EDE} = \exp(\mu_t + (1 - \eta)\sigma_t^2/2). \quad (1)$$

Without intragenerational inequality aversion ($\eta = 0$), EDE consumption equals mean consumption $c_t^{mean} = \exp(\mu_t + \sigma_t^2/2)$. If relative intragenerational inequality aversion equals one ($\eta = 1$), EDE consumption equals median per-capita consumption $c_t^{median} = \exp(\mu_t)$. In general, higher intragenerational inequality aversion and intragenerational inequality in consumption levels depress the EDE level of consumption. The Atkinson index increases in intragenerational inequality and aversion to it, and varies between zero (no intragenerational inequality or aversion to it) and 1 since $0 \leq I_t(\eta) = 1 - \exp(-\eta\sigma_t^2/2) < 1$. Dispersion in consumption drives median consumption below mean consumption. The standard deviation of consumption at time t is $\exp(\mu_t + \sigma_t^2/2) \sqrt{\exp(\sigma_t^2) - 1}$ and the corresponding coefficient of variation is $\sqrt{\exp(\sigma_t^2) - 1}$. The annualised growth rate of EDE consumption is defined as $g_t^{EDE} \equiv \ln(c_t^{EDE}/c_0^{EDE})/t$ and equals

$$g_t^{EDE} = [\mu_t - \mu_0 + (1 - \eta)(\sigma_t^2 - \sigma_0^2)/2] / t. \quad (2)$$

The annualised growth rates of median and mean consumption are $g_t^{median} = (\mu_t - \mu_0)/t$ and $g_t^{mean} = (\mu_t - \mu_0 + (\sigma_t^2 - \sigma_0^2)/2)/t$, respectively. Focusing on the median, the growth rate of the level of EDE consumption is given by

$$g_t^{EDE} = g_t^{mean} + \eta(g_t^{median} - g_t^{mean}) \quad (3)$$

(cf. Emmerling et al., 2017).¹ Hence, growth of EDE consumption increases in median growth, and decreases (increases) in mean growth if intragenerational inequality aversion exceeds (falls short of) one.

In the simplest case of *neutral* growth for all agents at the rate g , we have $\mu_t = \mu_0 + gt$ and $\sigma_t = \sigma_0$, $\forall t \geq 0$, so that $g_t^{mean} = g_t^{median} = g_t^{EDE} = g$, $\forall t \geq 0$. The coefficient of variation for the distribution of consumption levels at time t , i.e., $\sqrt{\exp(\sigma_t^2) - 1}$, is then constant over time. Neutral growth thus corresponds to a constant coefficient of variation for consumption levels. To obtain *non-neutral* growth where growth is associated with changes over time in the coefficient of variation of consumption levels, while keeping the average per-capita value unchanged, we suppose that the median is $\mu_t = \mu_0 + (g - h)t$ and that the variance is $\sigma_t^2 = \sigma_0^2 + 2ht$, $\forall t \geq 0$, with h a constant. This gives

$$g_t^{mean} = g, \quad g_t^{median} = g - h, \quad \text{and} \quad g_t^{EDE} = g - \eta h, \quad \forall t \geq 0. \quad (4)$$

For the Atkinson index of inequality, this implies $I(g) = 1 - e^{-\frac{\eta}{2}(\sigma_0^2 + 2ht)}$. The case $h > 0$ implies that intragenerational inequality in incomes grows over time, and the median of consumption growth is below mean growth. The coefficient of variation at time t is now $\sqrt{\exp(\sigma_0^2 + 2ht) - 1}$ and rises with time if $h > 0$.² In this situation growth is associated with rising intragenerational inequality. Alternatively, if $h < 0$, the coefficient of variation at time t falls over time, median consumption growth is above mean growth, and growth is associated with falling intragenerational inequality.

3 Social welfare with inter- and intragenerational inequality aversion

The quasi-concave function $V(c^{EDE})$ captures society's attitudes to intergenerational inequality aversion. We let $V(c^{EDE}) = ((c^{EDE})^{\omega-1} - 1) / (\omega - 1)$ if $\omega \neq 1$ and $V(c^{EDE}) = \ln c^{EDE}$ if $\omega = 1$. Here $\omega \equiv -c^{EDE}U''(c^{EDE})/U'(c^{EDE})$ denotes the constant coefficient of relative intergenerational inequality aversion. We assume that all agents have the

¹Instead of using the median, we can express EDE income growth also for any other quantile q other than the median ($q = 0.5$) of the lognormal distribution considered. In particular, we can express the growth rate of the EDE as $g_t^{EDE} = g_t^{mean} + \eta \frac{(g^q - g^{mean})}{(1 - \phi^{-1}(q))}$ (see Appendix A)

²The coefficient of variation can also be written as $\sqrt{(1 - I_t(\eta))^{-2/\eta} - 1}$.

same rate of time impatience or pure time preference $\delta > 0$. Within the expected utility framework, utilitarian social welfare is given by

$$\begin{aligned} W_0 &= \int_0^\infty e^{-\delta t} E \left[V \left(U^{-1} \left(\int_\theta U(c_t(\theta)) dF(\theta) \right) \right) \right] dt. \\ &= \int_0^\infty e^{-\delta t} E [V(c_t^{EDE})] dt \end{aligned} \quad (5)$$

This welfare function generalises Gollier (2015) by separating out the coefficients of relative intragenerational and intergenerational inequality aversion. This is important for the integrated assessment of climate policy (Dennig et al., 2015). The expected utility specification (5) implies that the coefficient of relative risk aversion equals the coefficient of intergenerational inequality aversion (i.e., the inverse of the elasticity of intertemporal substitution). Section 6 relaxes this assumption by extending equation (5) with recursive preferences (Kreps and Porteus, 1978; Epstein and Zin, 1989; Duffie and Epstein, 1992a,b). For the time being, we abstract from uncertainty (where the distinction does not matter) and use the welfare function $W_0 = \int_0^\infty e^{-\delta t} V(c_t^{EDE}) dt$.

Based on this welfare function and with non-recursive preferences, we consider two approaches for the marginal evaluation of consumption needed to derive the SDR and SCC. These approaches differ in the way marginal changes in consumption are distributed in the economy. The first approach considers a marginal change in the EDE level of consumption. Analytically, this EDE approach analyses a marginal change in the argument c_t^{EDE} of the function V in $W_0 = \int_0^\infty e^{-\delta t} V(c_t^{EDE}) dt$, i.e., dV/dc^{EDE} . This approach corresponds to a representative “EDE agent”, which decides on the intertemporal allocation of consumption, taking into account how inequality evolves over time but abstracting from the marginal impact of the project along the distribution at any point in time.

The second one is the “individual” approach, which is based on the first line of the welfare function given by (5) using as an argument the individual $c_t(\theta)$. It considers the inequality effect in the baseline over time but also explicitly assumes that the marginal changes in consumption arising from the costs and benefits of the project are equally shared among individual agents. Formally, marginal changes in consumption are evenly distributed at every point of the income distribution such that $dV/dc = \int_\theta (dV/dc(\theta_i)) d\theta$ and $\frac{dV}{dc(\theta_i)} = \varepsilon$ for all i .

The implications for the social discount rate are different for these two approaches. The following section assesses the relative merits of each approach and shows that the *EDE* approach is equivalent to Emmerling et al. (2017) while the *individual* approach is as

in Gollier (2015). The difference between the two approaches reflect different ways for the policy maker to take account of intragenerational inequality. In the EDE approach policy makers first take a stance on inequality aversion at a particular point of time, consider the EDE individual to be the representative agent, and then compare this agent's welfare over time. Whereas, the *individual* approach takes into account the (equal) marginal impact of the project along the full distribution, thus taking into account individual changes in marginal utility arising from the marginal costs and benefits of the project.

Neither approach assumes that there is a covariance between project impacts and marginal utilities along the income distribution at any point in time. Such covariances would lead to an *inequality-beta* type term in the discount rate and SCC (see Jacobs and van der Ploeg (2019) for an example and discussion of this possibility).

4 Adjusting the social discount rate for inequality

The SDR is defined as the rate of return to consumption, r_t , needed to forgo consumption today and preserve intertemporal welfare. Following (Gollier, 2011b, chapter 1), the social discount rate r_t is defined as

$$e^{-r_t t} = \frac{\partial W_0 / \partial c_t}{\partial W_0 / \partial c_0}. \quad (6)$$

4.1 The EDE approach

The EDE approach uses the welfare function shown in (5). Using equation (3), the SDR is based on the EDE level of consumption (cf. Dasgupta, 2008; Emmerling et al., 2017)

$$r_t^{EDE} = \delta + \omega g_t^{EDE} = \delta + \omega g_t^{mean} + \omega \eta (g_t^{median} - g_t^{mean}). \quad (7)$$

Upon substitution of the results in equation (4), this rule becomes

$$r_t^{EDE} = \delta + \omega (g - \eta h). \quad (8)$$

The adjustment for intragenerational inequality aversion is thus $\omega \eta (g_t^{median} - g_t^{mean})$.³ The conventional Ramsey rule gives the unadjusted SDR as $r_t^U = \delta + \omega g_t^{mean} = \delta + \omega g$,

³Emmerling et al. (2017) calculate median and average per capita growth rates for 25 countries over roughly three decades and find that median growth was below (above) average per capita growth in 15 (10) countries. Taking values for η of 1 (e.g., Stern, 2006) and 2 (e.g., Dasgupta, 2008), they calculate the adjustment for inequality to the SDR, i.e., for these countries. For the UK and US this effect depresses the SDR by about one percentage point if $\eta = 2$ but by roughly 0.25 percentage points if $\eta = 1$. For the Netherlands, this effect increases the SDR by 0.6%- and 0.2%-point, respectively.

where $\omega g_t^{mean} = \omega g$ is the unadjusted wealth effect. Growth in EDE consumption thus drives the SDR adjusted for intragenerational inequality. Growth in mean consumption drives the unadjusted SDR. The difference between the standard and inequality-adjusted SDR, i.e., $r_t - r_t^U = \omega\eta(g_t^{EDE} - g_t^{mean}) = -\omega\eta h$, is the product of (i) the welfare effect of changing intragenerational inequality, measured by the difference between EDE and mean consumption growth, i.e., $g_t^{EDE} - g_t^{mean} = -h$, multiplied by intragenerational inequality aversion, η ; and (ii) the coefficient of relative intergenerational inequality aversion, ω , which gives $-\omega\eta h$. Higher EDE growth implies that future generations are richer than current generations, so that society is less willing to invest in the future and employs a higher inequality-adjusted SDR, and more so if intergenerational inequality aversion ω is high. If economic growth is neutral and does not affect intragenerational inequality over time ($h = 0$), the unadjusted SDR is appropriate. If economic growth is associated with rising intragenerational inequality ($h > 0$), the SDR is adjusted downwards and more so the larger are the coefficients of relative intra- and intergenerational inequality aversion (as can be seen from the term $-\omega\eta h$).

Effectively, policymakers find the future more important relative to the present if intragenerational inequality rises over time, and the gap between mean and EDE consumption rises. The reason is that when inequality is increasing, the marginal utility of EDE consumption rises relative to that of mean consumption, making consumption in the future more valuable in the more unequal society. Conversely, if economic growth is associated with falling intragenerational inequality ($h < 0$), the social discount rate is adjusted upwards compared to the SDR based on mean consumption alone.

The analysis disentangles the intra- and intergenerational inequality aversion parameters, η and ω , respectively. Later we extend the analysis to uncertainty about the rate of economic growth and obtain a generalised expression for the SDR that also separates out society's attitude to risk aversion.

4.2 The individual approach

A discount rate based on recursive Epstein-Zin preferences is standard in the field of macro finance and has also been derived by Gollier (2002) and Traeger (2009). This leads to additional complexity due to the recursive definition of the utility function. In case of intragenerational inequality, a further level of complexity exists because inequality affects marginal utilities both today and in the future. For the lognormal case, we apply the

bivariate lognormal result of Emmerling (2018) and get

$$r_t^{ind} = \delta + \omega g_t^{mean} + (\omega + 1)g^{1-I_t(\eta)} \quad (9)$$

or

$$r_t^{ind} = \delta + \omega g_t^{EDE} = \delta + \omega g_t^{mean} + \omega \eta (g_t^{median} - g_t^{mean}), \quad (10)$$

which can also be written as

$$r_t^{ind} = \delta + \omega g - \eta(1 + \omega)h = \delta + \omega(g - \eta h) - \eta h. \quad (11)$$

Comparing the EDE approach in (8) with the SDR in the individual approach in (11), we see that the difference is the term $-\eta h$. This reflects a “prudence” or “downside inequality aversion” term, which takes into account that there is diminishing marginal utility for agents in the present and the future which is stronger among the poorer households.⁴ For the EDE representative agent, this prudence effect is absent.

5 The inequality-adjusted social cost of carbon

The SCC is the present discounted value of the stream of future damages from emitting one ton of carbon today. The value of the SCC depends on the welfare function, economic growth, and the ensuing accumulation of emissions and ensuing temperature change. In the following, D_t denotes global warming damages, T_t denotes temperature measured relative to its preindustrial level, and E_t denotes cumulative emissions, all at time t . Here e_0 denotes the emissions rate at time zero and N the number of agents in the economy. For simplicity, we abstract from population growth. Furthermore, we assume that global warming damages are proportional to aggregate economic activity (aggregate consumption) and linear in temperature increases, so that

$$D_t = (\chi_0 + \chi_1 T_t) N c_t^{mean}. \quad (12)$$

Here χ_1 denotes the marginal damage ratio, i.e., the increase in damages as proportion of aggregate output per degree Celsius of global warming, and χ_0 is a constant which may arise from linearising a nonlinear function of temperature. This relationship is consistent with recent empirical findings that the damage ratio is approximately linear in

⁴This reflects that with CRRA preferences, the third derivative of utility is positive ($U''' > 0$).

temperature change (e.g., Burke et al., 2015; Kalkuhl and Wenz, 2020).

Temperature is driven by cumulative emissions, so that

$$T_t = \xi_0 + \xi_1 E_t \text{ with } E_t = \int_0^t e_s ds. \quad (13)$$

Here e_s denotes the rate of fossil-fuel use measured in Giga tonnes of carbon and thus also the emissions rate at time s (e.g., Matthews et al., 2009; Allen et al., 2009; van der Ploeg, 2018; Dietz and Venmans, 2019), ξ_1 denotes the transient climate response to cumulative emissions, and $\xi_0 = \xi_1 E_0$ is a constant to capture the effect of historial emissions on temperature. The marginal effect of emitting one ton of carbon today on damages at time t in the future to all agents thus equals $\chi_1 \xi_1 N c_t^{mean}$. To evaluate this marginal effect in monetary terms today (using the definition of the SCC), we will specify a welfare function according to both the *EDE* and the *individual* approach.

In general, the SCC can be written using a definition similar in structure to the SDR in equation (3) except where the numerator reflects the discounted present value of future damages measured in utility, i.e.,

$$SCC_0 \equiv \frac{N \int_0^\infty e^{-\delta t} \left(\frac{\partial D_t}{\partial T_t} \right) \left(\frac{\partial T_t}{\partial E_t} \right) \left(\frac{\partial E_t}{\partial e_0} \right) \frac{\partial W_0}{\partial c_t} dt}{\partial W_0 / \partial c_0}. \quad (14)$$

This allows us to derive the SCC for different social welfare functions and their respective SDR formulae. With global warming damages and temperature change defined as above, the SCC can be written as

$$SCC_0^x = \frac{\chi_1 \xi_1 N c_0^{mean}}{R^x}, \quad (15)$$

where $R^x \equiv r_t^x - g$ denotes the growth-corrected social discount rate used to calculate the SCC. Here the superscript x is either *EDE* (see equation (8)) or *ind* (see equation (10) or (11)). The SCC thus equals the present discounted value of marginal present and future damages from emitting one ton of carbon today. This corresponds to current marginal damages divided by the SDR corrected for the rate of economic growth g to reflect that damages are proportional to economic activity and thus increase in line with economic growth.

5.1 The EDE approach

For the welfare function given by equation (5), the SCC ("The EDE approach") can be simply derived by the marginal impact on the welfare of the EDE agent today, i.e.,

$$SCC_0^{EDE} \equiv \frac{N \int_0^\infty e^{-\delta t} \left(\frac{\partial D_t}{\partial T_t} \right) \left(\frac{\partial T_t}{\partial E_t} \right) \left(\frac{\partial E_t}{\partial c_0} \right) V'(c_t^{EDE}) dt}{V'(c_0^{EDE})}. \quad (16)$$

Proposition 1. *The initial social cost of carbon under the EDE approach is*

$$SCC_0^{EDE} = \left(\frac{\chi_1 \xi_1}{\delta + (\omega - 1)g - \omega \eta h} \right) N c_0^{mean}, \quad (17)$$

where δ denotes the rate of time impatience, g the economic growth rate, ω the coefficient of relative intergenerational inequality aversion, η the coefficient of relative intergenerational aversion, h the difference between mean and median growth, χ_1 the increase in the damage ratio per degree Celsius of global warming, and ξ_1 the transient climate response to cumulative emissions.

Proof. Substituting relationships (12) and (13) into (16) and using (4), we get

$$SCC_0^{EDE} = N \int_0^\infty e^{-\delta t} \chi_1 c_t^{mean} \xi_1 \left(\frac{c_t^{EDE}}{c_0^{EDE}} \right)^{-\omega} dt, \quad (18)$$

which simplifies to equation (24). □

The denominator in the parentheses is the SDR minus the growth rate of consumption (as global warming damages are proportional to economic activity and grow at this rate). If economic growth does not affect intragenerational inequality over time (i.e., $h = 0$), equation (18) boils down to $SCC_0 = \left(\frac{\chi_1 \xi_1}{\delta + (\omega - 1)g} \right) N c_0^{mean}$. This is the usual expression for the SCC if intragenerational inequality is not taken into account. This SCC is proportional to aggregate economic activity, the marginal damage ratio, and the transient climate response to cumulative emissions, and inversely proportional to the unadjusted growth-corrected social discount rate ($r_t^U - g$). Higher impatience (δ) thus reduces the SCC. Furthermore, more concern about current generations being poorer than future generations (i.e., a higher intergenerational inequality aversion and higher growth, ωg)

increases the discount rate and depresses the SCC. Also, higher economic growth reduces the SCC if the coefficient of relative intergenerational inequality aversion exceeds one ($\omega > 1$), because then the wealth effect (ωg) dominates the effect of marginal damages growing in line with aggregate economic activity.

If economic growth is associated with rising intragenerational inequality ($h > 0$) as well rising intergenerational inequality (due to $g > 0$), the SDR in (7) is reduced and the SCC in (18) is increased, especially if inter- and intragenerational inequality aversion are high. If economic growth and growing intergenerational inequality go together with falling intragenerational inequality ($h < 0$), we have the opposite result in that the SCC (18) is reduced. The intuition behind this result is as follows. If economic growth is associated with rising (falling) intragenerational inequality, the level of EDE consumption grows slower (faster) than aggregate economic activity. Hence, the marginal utility of EDE consumption declines faster (slower) than that of mean consumption and thus the willingness to sacrifice consumption today to curb future global warming will be less (more) as reflected in a lower (higher) SDR. Inequality-increasing (increasing) growth reduces the SCC and leads to a more (less) ambitious climate policy with a higher (lower) price of carbon.

The EDE-based expression for the SCC yields a unique value of the social cost of carbon and in the absence of intergenerational inequality aversion ($\eta = 0$) collapses to the standard expression for the SCC.

5.2 The individual approach

Now we account for accounting for intragenerational inequality in the SCC at the individual level (the *individual* approach) by assuming that the costs are shared equally across citizens at different income levels. The *individual* approach yields individual estimates of the SCC for each point of the income distribution. This results in a distribution of SCC values for today's income distribution. The SCC is obtained by aggregating the welfare impacts across individuals, where the welfare value is normalised for each θ individual today. This gives the expression

$$SCC_{0,\theta}^{ind} \equiv \frac{N \int_0^\infty e^{-\delta t} \left(\frac{\partial D_t}{\partial T_t} \right) \left(\frac{\partial T_t}{\partial E_t} \right) \left(\frac{\partial E_t}{\partial e_0} \right) \frac{V'(\cdot)}{U'(\cdot)} \int_\theta U'(c_t(\theta)) dF(\theta) dt}{\frac{V'(\cdot)}{U'(\cdot)} U'(c_0(\theta))}. \quad (19)$$

The individual, (c_0) -specific SSC value is then computed as

$$SCC_{0,\theta}^{ind} \equiv \frac{N \int_0^\infty e^{-\delta t} \chi_1 c_t^{mean} \xi_1 (EU_t)^{\frac{\eta-\omega}{1-\eta}} \int_\theta c_0^{-\eta} dF(\theta) dt}{(EU_0)^{\frac{\eta-\omega}{1-\eta}} c_0^{-\eta}}. \quad (20)$$

Using the moments of the lognormal distribution, we can show that $SCC_{0,\theta}^{ind}$ becomes

$$SCC_{0,\theta}^{ind} = \frac{1}{c_0^{-\eta} / \int_\theta c_0^{-\eta} d\theta} \left(\frac{\chi_1 \xi_1}{\delta + (\omega - 1)g - \eta(1 + \omega)h} \right) N c_0^{mean}. \quad (21)$$

This value for the SCC is again proportional to aggregate output (see last term), reflects climate parameters and the individual discount rates (second term), and is normalised by the ratio of individual marginal utility at the level of consumption c_0 and the average level of marginal utility (first term). It follows that the SCC based on the *individual* approach is log-normally distributed across individuals as

$$SCC_{0,\theta}^{ind} \sim LN(\ln(SCC_0^{ind}) + \eta^2 \frac{\sigma_0^2}{2}, \eta^2 \sigma_0^2). \quad (22)$$

It thus has a higher mean than the SCC value under the EDE approach, and the difference scales quadratically in the coefficient of relative intragenerational inequality aversion. If policy makers have zero intragenerational inequality aversion ($\eta \rightarrow 0$), the three formulas collapse to the formula without intragenerational inequality.

The SCC based on the *individual* approach can be aggregated to obtain the economy-wide SCC, denoted by SCC_0^{ind} , under the assumption that each individual at $t = 0$ today pays the marginal project costs. The *individual* approach to the SCC evaluates the impact of the marginal project (or carbon emission) by comparing today's costs with future benefits, but also takes into account the distribution of its (assumed equal) distribution of costs today and benefits in the future. The aggregate SCC_0^{ind} reflects the total expected average welfare change under these assumptions and is given by

$$SCC_0^{ind} \equiv \frac{N \int_0^\infty e^{-\delta t} \left(\frac{\partial D_t}{\partial T_t} \right) \left(\frac{\partial T_t}{\partial E_t} \right) \left(\frac{\partial E_t}{\partial c_0} \right) \frac{V'(\cdot)}{U'(\cdot)} \int_\theta U'(c_t(\theta)) dF(\theta) dt}{\frac{V'(\cdot)}{U'(\cdot)} \int_\theta U'(c_0(\theta)) dF(\theta)}. \quad (23)$$

Proposition 2. *The initial social cost of carbon under the individual approach is*

$$SCC_0^{ind} = \left(\frac{\chi_1 \xi_1}{\delta + (\omega - 1)g - \eta(1 + \omega)h} \right) N c_0^{mean}, \quad (24)$$

where δ denote the rate of time impatience, g the economic growth rate, ω the coefficient of relative intergenerational inequality aversion, η the coefficient of relative intergenerational aversion, h the difference between mean and median growth, χ_1 the increase in the damage ratio per degree Celsius of global warming, and ξ_1 the transient climate response to cumulative emissions.

Proof. Use the assumptions on temperature change and associated climate damages in equation (20) to get the result. □

The only difference between SCC_0^{ind} and SCC_0^{ede} is the prudence term $-\eta h$ in the SDR given in equations (11) and (8), respectively. This arises because of the assumption that all damages and costs are born equally by each individual along the distribution in the *individual* approach. The SCC_0^{ind} can also be written as a weighted average of the individual SCC for each individual in the population, i.e.,

$$SCC_0^{ind} = \frac{c_0^{-\eta}}{\int_{\theta} c_{0,\theta}^{-\eta} d\theta} SCC_{0,\theta}^{ind}. \quad (25)$$

We thus establish that SCC_0^{ind} is an equity-weighted estimate of the SCC (cf. Anthoff et al., 2009; Hope, 2008; Watkiss and Hope, 2011; Anthoff and Emmerling, 2019; Nordhaus, 2011) with equity weights as derived in Fankhauser et al. (1997).

Compared to the EDE approach, the individual approach thus introduces a arbitrary “normalisation” to a particular level of c_0 , while the EDE level of consumption is a natural candidate given the welfare definition in equation (5).

5.3 What if global warming hurts the poor more than the rich?

The damages equation (12) does not capture that global warming hurts the poor more than the rich, but rather that the *relative* income loss is equal throughout the income distribution (cf. Dennig et al. (2015) for a unity elasticity of damages).⁵ However, empirical

⁵If equity weights are applied both across space and time, the effects of equity weighting on the SCC can be significant and will depend on factors such as different growth rates for different regions or nations (e.g., Anthoff et al., 2009; Nordhaus, 2014). Depending on the assumed intraregional income distribution, estimates of the equity-weighted SCC may be more than twice as high if national rather than regional impacts are used (Anthoff et al., 2009). Equity weights based on a social welfare function

evidence suggests that poorer countries suffer the brunt of climate change. Furthermore, poorer households in rich societies are also more adversely affected by global warming. If societies have a greater intragenerational inequality aversion and account is taken of the fact that the poor are hurt more by global warming damages than the rich, the equity-weighted SCC is higher (Mirrlees, 1978; Jacobs and van der Ploeg, 2019). In principle one could use consumption after global warming damages to define EDE consumption to capture this effect. If the poor are hurt relatively more than the rich by damages stemming from global warming, then it can be shown that EDE consumption corrected for global warming damages will be lower (see Appendix B). Assuming that the distribution of the costs and benefits of the climate mitigation investment remain constant, a regressive distribution of climate damages is isomorphic to increasing intragenerational inequality. This implies that the SCC evaluated under the EDE approach is higher.

6 Adjusting the SCC for intra- and intergenerational inequality and economic uncertainty

The EDE approach has an intuitive social welfare function (see equation (5)) and provides a simple and natural framework within which to introduce uncertainty and catastrophic impacts. In this section we use this approach and model uncertainty in the development of per-capita (mean) consumption with a stochastic diffusion process. In particular, we consider uncertainty about future economic growth prospects and assume that the stochastic process for mean consumption is given by geometric Brownian motion with drift. Hence,

$$dc_t^{mean} = \vartheta c_t^{mean} dt + v c_t^{mean} dW_t, \quad (26)$$

where ϑ denotes the drift, v denotes the volatility, and W_t is a unit Wiener process. The stochastic process (26) has the solution $c_s^{mean} = c_t^{mean} \exp((\vartheta - v^2/2)(s - t) + vW_s)$. where the expected value equals $E_t[c_s^{mean}] = e^{\vartheta(s-t)} c_t^{mean}$ and $E_t(\ln c_s^{mean} / \ln c_t^{mean}) = (\vartheta - v^2/2)(s - t)$ and time-varying variance $var(c_s^{mean}) = e^{2\vartheta(s-t)}(e^{v^2(s-t)} - 1)(c_t^{mean})^2$, $\forall s \geq t$. To allow for a coefficient of relative risk aversion, γ , that is separate from the coefficient of intergenerational inequality aversion, ω , we adopt recursive preferences (Kreps and Porteus, 1978; Epstein and Zin, 1989; Duffie and Epstein, 1992a,b). The social welfare

and attitudes towards equity and justice have been used to allow for international equity weights where from the standpoint of which cost of carbon to use by national policymakers it is crucial to weigh liability towards foreigners correctly (e.g., Anthoff and Tol, 2010)

function is then no longer given by the expected utility specification (5), but by the recursive formulation

$$W_t = E_t \left[\int_t^\infty f(c_s^{EDE}, W_s) ds \right] \quad \text{with} \quad f(c_t^{EDE}, W_t) = \delta \theta W \left[\frac{(c_t^{EDE})^{1-\omega}}{((1-\gamma)W_t)^{\frac{1}{\theta}}} - 1 \right]. \quad (27)$$

For $\omega = 1$ the aggregator function is $f(c_s^{EDE}, W_s) ds = \delta(1-\gamma)W \ln \left(\frac{c_s}{[(1-\gamma)W_s]^{1/(1-\gamma)}} \right)$. Here ω denotes the coefficient of intergenerational inequality aversion (or inverse of the elasticity of intertemporal substitution) as before and γ the coefficient of relative risk aversion. If the coefficient of relative risk aversion exceeds that of intergenerational inequality aversion, policymakers prefer early resolution of uncertainty. Instead of using the growth-corrected interest rate $R^{EDE} = r_t - g$ with r_t the deterministic SDR given in equation (8) and $g = \vartheta$, Appendix C shows that the discount rate used to calculate the SCC now equals

$$\begin{aligned} R^{EDE} = & \underbrace{\delta}_{\text{impatience}} + \underbrace{\omega\vartheta}_{\text{affluence}} - \underbrace{\omega\eta h}_{\text{rising inequality}} - \underbrace{\vartheta}_{\text{rising damages}} - \underbrace{\frac{1}{2}(1+\omega)\gamma v^2}_{\text{prudence}} + \underbrace{\gamma v^2}_{\text{insurance}} \\ & = \delta + (\omega - 1) \left(\vartheta - \frac{1}{2}\gamma v^2 \right) - \omega\eta h. \end{aligned} \quad (28)$$

The SDR consists of the usual *impatience* and *wealth/affluence* effects and a negative term to reflect the *rising intragenerational inequality* of incomes associated with growth of the economy. It also has a negative term to correct for global warming *damages rising* in line with growth of the economy. In a stochastic world there are two further terms. First, a *prudence* effect which depresses the SDR especially if the coefficient of relative prudence $(1 + \omega)$, risk aversion (γ) and volatility of economic growth are high (Kimball, 1990; Leland, 1968). Second, an *insurance* effect which captures that in future states of nature economic growth is associated with high global warming damages (which are proportional to aggregate economic activity). This leads to a higher SDR and discount rate to calculate the SCC, reflecting this systematic consumption risk and insurance motive.⁶ The SCC corresponding to the discount rate (28) is thus given by

$$SCC_0 = \left(\frac{\chi_1 \xi_1}{\delta + (\omega - 1)(\vartheta - \gamma v^2/2) - \omega\eta h} \right) N c_0^{\text{mean}}, \quad (29)$$

⁶Without the rising inequality and insurance terms, the SDR becomes $r_t = \delta + \omega\vartheta - \omega v^2/2$ if the coefficient of relative risk aversion coincides with the coefficient of relative intergenerational inequality aversion, i.e., $\gamma = \omega$ (Gollier, 2011a; Arrow et al., 2014).

where the denominator of this expression is given by the return on risky assets minus the rate of economic growth, i.e., $R = r_t - \vartheta$.

Equation (29) can be extended into two directions. The first one is to make damages proportional to $(Nc_t^{mean})^\beta$, where β is the so-called climate beta which we have so far assumed to be unity (cf. Dietz et al., 2018). The case where damages are proportional to aggregate economic activity (i.e., “multiplicative” damages) corresponds to $\beta = 1$ and the case where damages are unrelated to aggregate economic activity (“additive” damages) corresponds to $\beta = 0$. For general β , the discount rate given in equation (28) becomes

$$R = \underbrace{\delta}_{\text{impatience}} + \underbrace{\omega\vartheta}_{\text{affluence}} - \underbrace{\vartheta}_{\text{rising damages}} - \underbrace{\omega\eta h}_{\text{rising inequality}} - \underbrace{\frac{1}{2}(1+\omega)\gamma v^2}_{\text{prudence}} + \underbrace{\beta\gamma v^2}_{\text{insurance}} \quad (30)$$

$$= \delta + (\omega - \beta)(\vartheta - \eta h) - \frac{1}{2}(\omega + 1 - 2\beta)\gamma v^2$$

(see end of Appendix C). A climate beta less than one depresses the insurance effect and hence also depresses the SDR. Dietz et al. (2018) argue that the climate beta is close to unity for maturities up to one hundred years.⁷ The SCC corresponding to (30) becomes

$$SCC_0 = \left(\frac{\chi_1 \xi_1}{\delta + (\omega - \beta)(g - \eta h) - \frac{1}{2}(\omega + 1 - 2\beta)\gamma v^2} \right) Nc_0^{mean}, \quad (31)$$

where the denominator of this expression equals R . Note that if $\beta = 1$, equation (31) boils down to equation (29). If damages are less than proportional to economic activity, i.e., $\beta < 1$, the denominator R is higher and the SCC lower than if $\beta = 1$ provided $\vartheta - \eta h > \gamma v^2$. In that case, the negative effect on the SCC of damages growing less rapidly than the economy dominates the positive effect on the SCC of the insurance terms being smaller.

The second extension of equation (29) is to allow for the risk of rare macroeconomic disasters as well as for conventional macroeconomic risks (captured by geometric Brownian motion) on the growth rate of the economy (e.g., Barro, 2006). Disasters occur with probability λ and destroy a proportion l of mean consumption. The recovery ratio is denote by $Z \equiv 1 - l$. The generalised expression for the discount rate used to calculate

⁷The positive effect on this beta of uncertainty about exogenous, emissions-neutral technical change swamps the negative effect on this beta of uncertainty about the climate sensitivity and the damage ratio. Mitigating climate change thus increases aggregate consumption risk and calls for a higher SDR for discounting expected benefits of emission cuts. But the stream of undiscounted expected benefits also increases in this beta and this dominates the effect on the SDR.

the SDR (see Appendix C) (28) becomes

$$R = \delta + (\omega - 1) \left(\vartheta - \eta h - \frac{1}{2} \gamma v^2 \right) - \lambda \left(E[Z^{-\gamma} - 1] + \left(\frac{\omega - \gamma}{\gamma - 1} \right) (E[Z^{1-\gamma}] - 1) \right). \quad (32)$$

We assume that the recovery fraction has a power distribution $f(Z) = \alpha Z^{\alpha-1}$ defined on the interval $Z \in (0, 1)$ with $\alpha > 0$.

Proposition 3. *The initial social cost of carbon under the EDE approach adjusted for both inequality and for normal and rare disaster risks in the rate of economic growth with damages proportional to economic activity, i.e., $\beta = 1$, equals*

$$SCC_0 = \frac{\chi_1 \xi_1 N c_t^{mean}}{\delta + (\omega - 1) \left(\vartheta - \eta h - \frac{1}{2} \gamma v^2 \right) - \lambda \left(E[Z^{-\gamma} - 1] + \left(\frac{\omega - \gamma}{\gamma - 1} \right) (E[Z^{1-\gamma}] - 1) \right)}. \quad (33)$$

where ϑ denotes the drift and v the volatility of the geometric Brownian consumption for individual consumption, λ the probability of a macroeconomic disaster, and Z the fraction of consumption that remains after a disaster. The denominator of this expression equals the growth-corrected discount rate R . If the fraction remaining after a shock follows a power distribution, we can substitute $E[Z^{-\gamma}] = \alpha/(\alpha - \gamma)$ and $E[Z^{1-\gamma}] = \alpha/(\alpha + 1 - \gamma)$ into the expressions for R and SCC_0 .

Proof. The result follows from equation (32) when $\beta = 1$. □

This expression for the SCC allows for intra-generational and intergenerational inequality aversion and for risk aversion. It takes care of widening inequality arising with growth (via the term $-(\omega - 1)\eta h$), conventional macro risks (via the term $-(\omega - 1)\gamma v^2/2$), and the risk of rare macroeconomic disasters (via the last term in the denominator).

7 Calibration

We now calibrate our model before quantifying our analytical expression for the SCC using a range of values for the coefficients of relative intra- and intergenerational inequality aversion and risk aversion. We assume a rate of pure time preference of 2% per year ($\delta = 0.02$), and an average growth of per-capita consumption of 2.0% per year ($g = 0.02$), which is the average growth rate of global GDP in the “middle of the road” projection of the Shared Socioeconomic Proposals (SSPs) over the 21st century (SSP2), see Riahi

et al. (2017).⁸ Moreover, we use the World Development Indicators (WDI) for data on GDP, population, PPP exchange rates and, using 2015 as base year, we use a population $N = 7.28$ billion and a per-capita level of global GDP (using 2005 \$USD[PPP]) of $c_0^{mean} = \$13,993$ in 2015.

Quantification of the SCC also requires estimates of the central parameters of our analysis of intragenerational inequality, i.e., inequality aversion ω and the change in inequality h . On global income inequality, we first construct a country-level dataset on household deciles combining data for about 155 countries based on the UNU-WIDER World Income Inequality Database (WIID) and data from Lakner and Milanovic (2016) and Milanovic (2016). We then compute the world distribution of income among all citizens (Concept 3 inequality of Lakner and Milanovic (2016) and Milanovic (2016)), and compute the average Gini and coefficient of variation over the last thirty years until 2019. We find that after a rise after 1990, inequality at this level has been almost steadily declining. This latter effect is largely due to economic growth in China and other emerging economies, yet over the last years the decline in inequality has slowed down. The global Gini index declined from about 0.7 to 0.63 up to 2010 (in line with the estimates of Milanovic (2012)), then declined further to about 0.59 in 2015. In particular, for 2015, we estimate a coefficient of variation of $CV_0 = 1.41$. Based on the WDI and SWIID statistics for 2015, we thus initialise our distribution by the parameters $\mu_0 = 8.98$ and $\sigma_0^2 = \ln(1 + CV_0^2) = 1.100163$. These estimates characterise the initial income distribution and hence inequality in the global economy.

With regard to changes in inequality, h , we first compute the world income distribution combining country-level population and GDP projections from Riahi et al. (2017). These are combined with historical household income deciles and projections of future income inequality based on Rao et al. (2019). From this we obtain global projections of changes in income inequality for the 21st century. Our best-guess estimate reproduces the inequality level of the average historical trends scenario (SSP2) in 2100 reaching a lower global Gini index of about 0.51. In this scenario growth is inequality-reducing, leading to our central estimate ($h = -0.0043$) (see the dotted lines in Figure 1). We develop two further scenarios for sensitivity. The first assumes a slow increase inequality, so that h is positive ($h = 0.0006$) as in SSP4. The second assumes a faster decline in inequality than the central case ($h = -0.011$), which reflects the trend in the last decade (indicated by the dashed lines in Figure 1). Figure 1 illustrates the SSP scenarios and what our linear

⁸An annual rate of 2% also reflects the view of experts on social discounting from the economics profession found in Drupp et al. (2018)

characterisation of the associated changes in inequality implies for our three scenarios.

Figure 2 shows that recent empirical estimates of global damages as proportion of GDP can be approximated reasonably well by linear functions in temperature change. Each dashed line in Figure 2 gives an empirical relationship between the damages as percentage of GDP versus temperature for a variety of studies. The solid lines are the linear approximations to these dashed line for each study. These approximations have been estimated using linear regressions for the temperature range 1-4 degrees Celsius, where in each case the estimated linear regression function is constrained to have the same value at 1 degree Celsius as the empirical (dashed) damage functions.

Between 0 and 1 degrees Celsius the dashed and solid lines coincide, and the linear approximation (solid line) connects to the empirical functions at 1 degrees Celsius. The linear approximations are accurate in this range, particularly for studies 3) and 4). Beyond 4 degrees Celsius, studies 1) and 2) begin to diverge due to their quadratic nature. We focus on the range between 1 and 4 degrees Celsius as the policy relevant range, but note that the analysis could be extended beyond 4 degrees Celsius. Within this range, the R-squared for each study is above 95%. For the calibration in this paper, we use the damage function given by Kalkuhl and Wenz (2020) (in red), which results in $\chi_1 = 0.0345$ or a loss of 3.5% of GDP per degree of global warming.

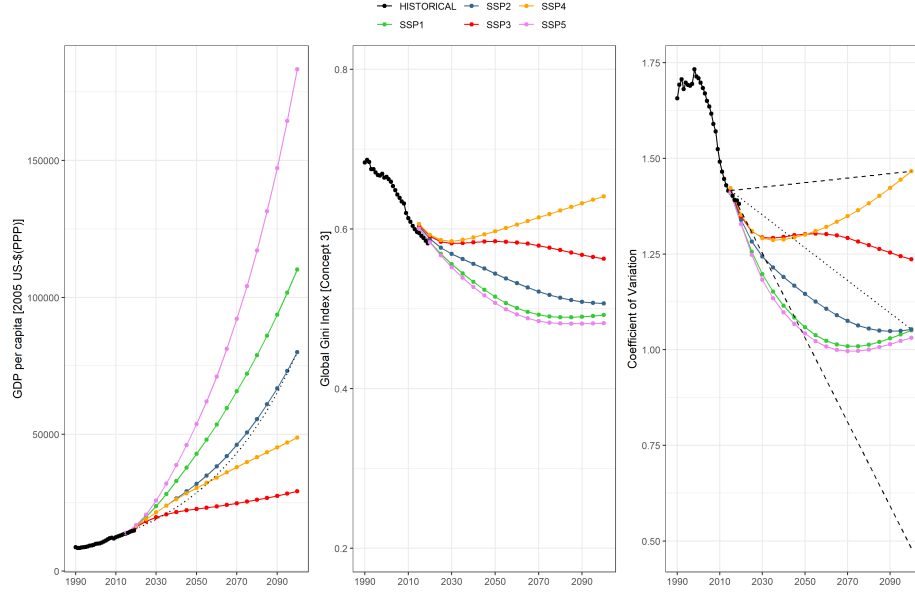


Figure 1: Historical GDP per capita and inequality and for different SSPs Each panel shows historical trends from 1990 until 2020 in, from left to right; per capita GDP, the Gini coefficient and the coefficient of variation. In each case projections from 2020 to 2100 based on the SSP scenarios. For the coefficient of variation, the dotted lines reflect the linear trend assumed to calibrate h in our estimates of the SCC.

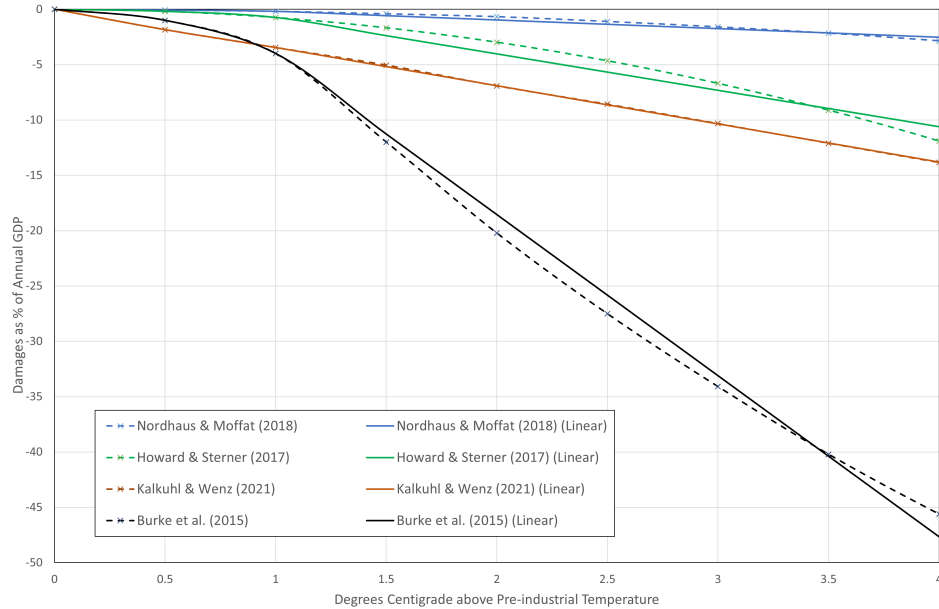


Figure 2: Estimates of Climate Damages as a Proportion of GDP and their Linear Approximations. The figure shows empirical global damage functions from four influential papers on the estimation of climate damages which are routinely referred to in integrated assessment studies: i) Nordhaus and Moffat (2017); 2) Howard and Sterner (2017); 3) Burke et al. (2015); and, 4) Kalkuhl and Wenz (2020). 1) and 2) are meta-analyses, 3) and 4) stem from the new climate econometrics literature and use detailed micro-granular data to establish the relationship between GDP/GDP growth and weather data.

With regard to the climate and impacts we use a transient climate response to cumulative emissions of 1.8 degrees Celsius per trillion tons of carbon. This value is at the center of the "likely" range (1.0–2.5°C) of IPCC 5th Assessment Report (AR5). To estimate the marginal damage function we draw from several sources. Nordhaus (2017) calibrated the damage ratio as 0.236% loss in global income per degree Celsius squared, so the marginal damage ratio is 0.944%, 2.1% and 8.5% of world GDP at, respectively, 2, 3 and 6 degrees Celsius relative to the preindustrial level. As shown in Figure 2 more recent literature tends to suggest a linear relationship between temperature and damages as a proportion of GDP. For our central estimates we use a linear approximation of the damage function estimated by Kalkuhl and Wenz (2020) (see Figure 2, which lies in between the extremes of Nordhaus (2017) and Burke et al. (2015)). This results in $\chi_1 = 0.0345$ or damages of about 3.5% of GDP for each degree Celsius of global warming.

8 Quantification of the social cost of carbon

8.1 Deterministic results

Table 1 reports the results for the SDR and the SCC for the deterministic case without macroeconomic uncertainty or catastrophic risks. Consider the benchmark case with unit coefficients of relative intra- and intergenerational inequality aversion ($\eta = \omega = 1$). If economic growth does not affect intragenerational inequality ($h = 0$), the SCC is \$85/tCO₂. If growth is associated with slow convergence in income per capita as estimated in our middle of the road scenario (SSP2) with $h = 0.05$, the SDR increases while the SCC is reduced to \$70/tCO₂ (and further to \$55/tCO₂ for a very fast convergence in incomes per capita). However, if economic growth is associated with increasing inequality per year ($h = 0.0006$), the SDR decreases and the SCC rises to \$88/tCO₂.

The effects of intragenerational inequality aversion η are as follows. If economic growth is neutral and does not affect intragenerational inequality, the parameter η is irrelevant for the SDR and the SCC. However, if economic growth is inequality-increasing ($h > 0$), then reducing the coefficient of relative intragenerational inequality aversion from 1 to 0.5 curbs the SCC slightly from \$88/tCO₂ to \$86/tCO₂. The reason is that with lower aversion to intragenerational inequality the growth in EDE consumption is lower and thus the decline in marginal utility of EDE consumption is lower too. The welfare effects of inequality are lower, leading to a lower SCC and a less ambitious climate policy. Conversely, if intragenerational inequality aversion is increased from 1 to 1.5, the SCC increases slightly.

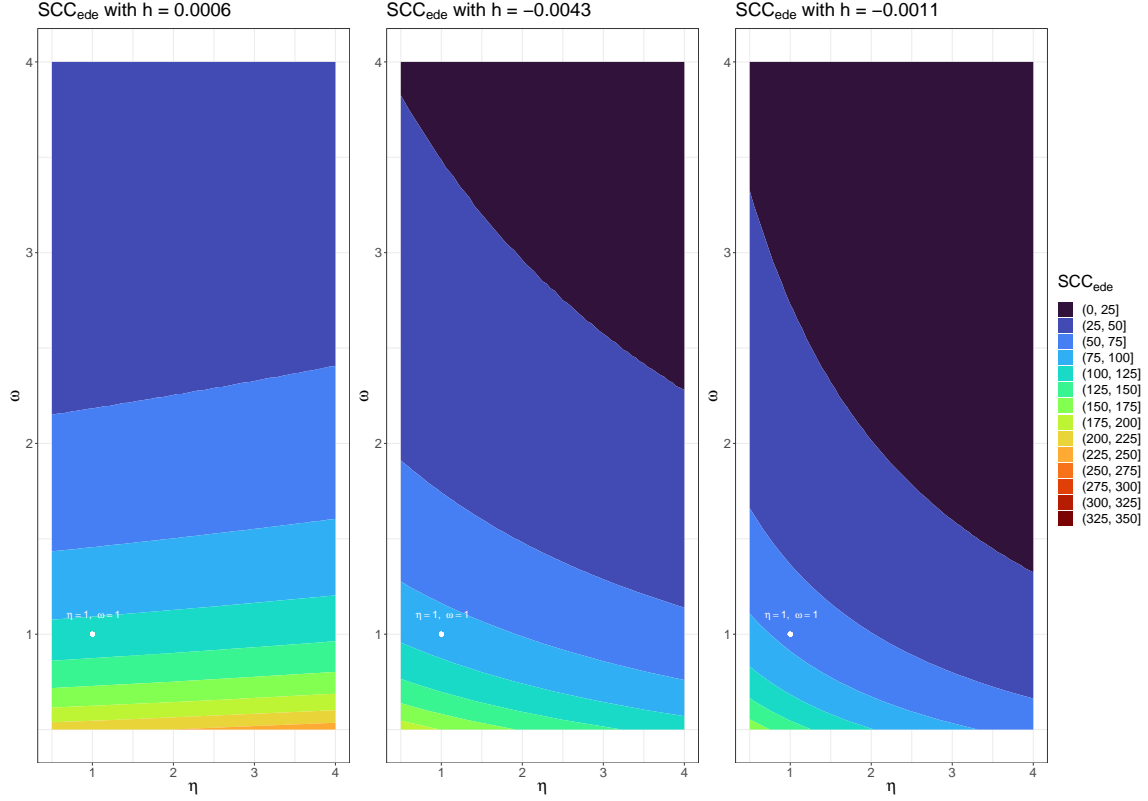


Figure 3: The SCC as function of intragenerational (η) and intergenerational inequality aversion (ω) without stochastic shocks to the economy. The SCC is calculated from equation (16)–the EDE approach. SSP4 has inequality-increasing growth and is approximated by $h = 0.006$. SSP2 has inequality-decreasing growth and is approximated by $h = -0.0043$. SSP1 has sharply inequality-decreasing growth and is approximated by $h = -0.011$.

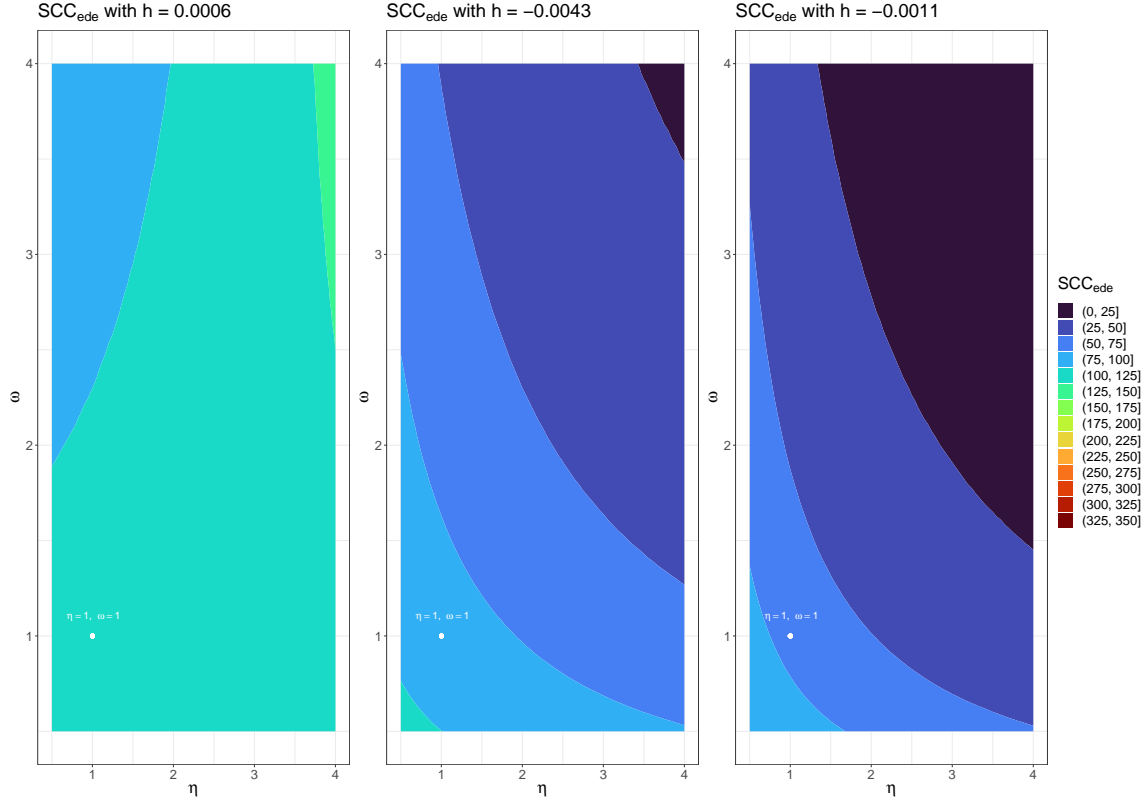


Figure 4: The SCC as function of intragenerational (η) and intergenerational inequality aversion (ω), with stochastic growth of the economy. The SCC is calculated from equation (33)–the EDE approach. Macroeconomic risk (geometric Brownian motion) has drift $\vartheta = 2.5\%$ /year, volatility $v = 2\%/\sqrt{\text{year}}$, and disaster risk probability is $\pi = 1.7\%$ /year, with size $E[d] = 0.29\%$ ($E[(1-d)^{-4}] = 7.69$ and $E[(1-d)^{-3}] = 4.05$). $\delta = 2.0\%$ /year, relative risk aversion to $\gamma = 4$, the elasticity of intertemporal substitution $1/\omega = 2$. The SSP4 scenarios are as in Figure 3

Table 1: Social Cost of Carbon for different specifications [\$/tCO₂], deterministic results

η	ω	SCC_{ind}				SCC_{ede}			
h	=	0.0006	0	-0.0043	-0.011	0.0006	0	-0.0043	-0.011
1	1	90.4	85	59.4	40.5	87.6	85	69.9	54.8
0.5	1	87.6	85	69.9	54.8	86.3	85	76.7	66.6
1.5	1	93.4	85	51.7	32.1	89	85	64.3	46.6
1	0.5	186.8	170	103.3	64.1	175.2	170	139.9	109.6
1	1.5	59.6	56.7	41.7	29.6	58.4	56.7	46.6	36.5

Now less (more) intragenerational inequality aversion leads to a lower (higher) SDR and a higher (lower) SCC. The reason for this opposite result is that policymakers faced with falling inequality over time, faster rising EDE consumption, and a faster decline of the marginal utility of EDE consumption, choose to have a more (less) ambitious climate policy.

The effects of intergenerational inequality aversion, ω , are as follows. If economic growth does not affect intragenerational inequality ($h = 0$), more intergenerational inequality aversion raises the social discount rate and thus reduces the SCC. If economic growth goes together with rising (falling) inequalities in per-capita consumption, this effect is qualitatively the same except that the SCC values are higher (lower). These complex relationships are summarised in Table 1 and Figure 3 for each of our three inequality-growth scenarios. With regard to the differences between the *individual* and the EDE approach, Figure 5 in Appendix D shows how the SCC under the individual approach varies in a similar way with ω and η . Note that the differences between these two approaches are generally relatively small (less than 5%). We favour using the EDE approach in part because it is more tractable, but also because the assumption that intragenerational inequality is assessed and internalised in each period by the EDE income seems closer to the way in which a policy maker assesses societal inequality in practice.

8.2 Stochastic results

We follow the calibration of Barro (2009) which attempts to explain the equity-premium puzzle with a relatively high value of risk aversion (γ) compared to the elasticity of intertemporal substitution and with risk of rare macroeconomic disasters. The conventional macroeconomic risk (captured by geometric Brownian motion) is calibrated with a drift of $\vartheta = 2.5\%$ /year and a volatility of $v = 2\%/\sqrt{\text{year}}$. The macroeconomic disaster risk is calibrated so that the probability of a macroeconomic disaster is $\pi = 1.7\%$ /year and

Table 2: Social Cost of Carbon under the EDE approach [\$/tCO₂], stochastic results

η	ω	SCC_{ede}			
h	=	+0.0006	0	-0.0043	-0.011
1	1	87.6	85	69.9	54.8
0.5	1	86.3	85	76.7	66.6
1.5	1	89	85	64.3	46.6
1	0.5	88.4	87.1	78.4	67.9
1	1.5	86.8	83	63.1	46

the expected size of a macroeconomic disaster is 1.5% ($l = 0.015$), which for the power function distribution yields a parameter of $\alpha = 65.66$. Furthermore, relative risk aversion is set to $\gamma = 4$. For $h = 0$, this calibration implies that an increase in the volatility ϑ by 10% requires an increase of 0.38% in endowment for all years to be compensated for the increase in uncertainty. For a 10% increase in disaster risk, this figure for the compensation endowment rises to 2.6% each year.

To illustrate the effects of conventional macroeconomic uncertainty and the risk of macroeconomic disasters on the SCC, Table 2 presents similar results as Table 1 highlighting the effects of changing intragenerational inequality alongside different levels of intragenerational inequality aversion.

For a value of $\omega = 1.5$ as in DICE, we see that with inequality-neutral growth the SCC \$57/tCO₂ in the deterministic case to \$84.6/tCO₂ with macroeconomic growth and catastrophic macroeconomic risks, an increase of almost 50%. With intragenerational inequality declining over time, this impact is reduced, and at $h = -0.0011$, the SCC falls from \$36/tCO₂ to \$45/tCO₂ and the markup is thus only 25%. On the other hand if $\omega = 0.5 < 1$, the uncertainty affect on the discount rate is negative and lowers it by approximately half. With inequality-neutral growth, the SCC drops from \$170/tCO₂ to \$83/tCO₂. Note that for logarithmic intertemporal utility ($\omega = 1$), the uncertainty about the rate of economic growth does not affect the SCC, which highlights the importance of disentangling the different degrees of aversion to intertemporal fluctuations, intragenerational inequality and risk in the welfare functions used.

9 Conclusion

We have shown how the social discount rate and the social cost of carbon can be adjusted to allow for intra and intergenerational inequality in society and for intra and intergenerational inequality aversion. The result is a novel and highly tractable formula for the

SCC. We have used this formula to calculate the SCC calibrated to updated estimates of the climate damage function based on Kalkuhl and Wenz (2020). In addition, we have extended our results to allow for uncertainty in the growth of mean per-capita consumption over time, and the risk of macroeconomic disasters. This allows us to identify the most important determinants of the SDR and the SCC, and the relative importance of inequality and inequality aversion, both inter- and intragenerational, compared to risk and uncertainty.

Our main insights are that, if economic growth is associated with rising (falling) intragenerational inequality, the social discount rate is lower (higher) and the social cost of carbon higher (lower) than it would be compared to a scenario where economic growth does not change intragenerational inequality over time. These effects increase with the coefficients of intra and intergenerational inequality aversion. Based on historical data on the global income distribution showing an inequality-reducing trend since the 1990s, we have estimated several scenarios of inequality and economic growth over the 21st century, and argue that a (slow) continuation of this trend seems most probable. This trend results in a reduction of the social cost of carbon from \$85 to \$70 per ton of CO_2 in our main specification.

Concerned policymakers find the future more (less) important relative to the present as intragenerational inequality rises (falls) over time, and the gap between mean and Equally Distributed Equivalent (EDE) consumption grows over time. Higher intergenerational inequality aversion increases the effect of the trend growth of mean consumption on the social discount rate and thus reduces the SCC. However, intergenerational inequality aversion also amplifies the negative effects of macroeconomic uncertainty and disaster risk on the risk-free social discount rate and thus increases the SCC, especially if the volatility of macro uncertainty is high and macro disaster risk is large.

We have put forward a generalised framework for evaluating the social discount rate and the social cost of carbon under various types of inequality and risk, which can nevertheless be further extended in various directions. First, our analysis can be improved by considering inequality between and within countries. Future work could also use more realistic distributions than the lognormal. For example, while the lognormal provides analytically convenient expressions, the Pareto distribution may be used to better capture the top tails of the income distribution. Such extensions will require numerical evaluation of the SCC. Second, damages from global warming might be a nonlinear function of temperature and of cumulative emissions. In that case, a perturbation method or a

numerical algorithm must be used. Third, as shown in Appendix B, global warming might hurt the poor more than the rich. The calculation of the SCC should take this into account with a more detailed calibration. Furthermore, just as our approach has taken into account catastrophic risks across time, future models ought to assess the the prospect of catastrophic damages to households or countries with already low incomes, which would increase the welfare effects of climate change. Fourth, the social discount rate may decline with the length of the horizon.

We abstract from persistence in the growth dynamics and uncertainty about the drift or volatility parameters, which could lead to a declining term structure of discount rates (Gollier 2008, 2013; Freeman and Groom, 2016). Nevertheless, by using the certainty-equivalent social discount rate, which embodies the uncertainty in, and persistence of, future growth rates one could then calculate the social cost of carbon (see e.g. Newell et al., 2022 for a proposal).

This occurs if the discount rate is constant but uncertain as then the certainty-equivalent value of the social discount rate will be falling over time

⁹ Fifth, a heterogeneous-agent model of the macro-economy augmented with a climate block in which the distributions of incomes and wealth evolve endogenously together with the accumulation of capital is more realistic than an endowment economy. ¹⁰ Finally, it is important to investigate how carbon pricing and in particular the recycling of revenues can affect inequality and thus welfare outcomes and how this should affect the optimal environmental policies to be implemented in practice (e.g., Klenert et al., 2018). This paper provides a foundation for these proposed extensions.

References

Achdou, Yves, Jiequn Han, Jean-Michel Lasry, Pierre-Louis Lions, and Benjamin Moll, “Income and Wealth Distribution in Macroeconomics: A Continuous-Time Approach,” *The Review of Economic Studies*, April 2021, 1.

⁹A declining term structure can arise when interest rates (e.g. Weitzman, 1998; Newell and Pizer, 2003; Weitzman, 2007; Freeman et al., 2015) or consumption growth (e.g. Vasicek, 1977; Gollier, 2011b) exhibit persistence over time, provided the social welfare function exhibits prudence. Parameter uncertainty in the growth process can also lead to a declining term structure (Gollier et al., 2008). See Newell et al. (2022) for a recent application of these principles to the estimation of the SCC.

¹⁰The heterogeneity can lead to intragenerational distribution of income and wealth (Achdou et al., 2021) or across overlapping generations (e.g., Kotlikoff et al., 2021). Recently, second-best climate and fiscal policies has been analysed in an intertemporal macroeconomic model with heterogeneous agents which finds that the time path of the second-best optimal carbon tax is lower than that of the first-best optimal carbon tax due to the marginal cost of public funds being driven above unity by distorting taxes on labour and/or capital income.(Douenne et al., 2022)

- Aldy, Joseph E., Matthew J. Kotchen, Robert N. Stavins, and James H. Stock**, “Keep climate policy focused on the social cost of carbon,” *Science*, 2021, *373* (6557), 850–852.
- Allen, Myles R., David J. Frame, Chris Huntingford, Chris D. Jones, Jason A. Lowe, Malte Meinshausen, and Nicolai Meinshausen**, “Warming caused by cumulative carbon emissions towards the trillionth tonne,” *Nature*, April 2009, *458* (7242), 1163–1166.
- Anthoff, David and Johannes Emmerling**, “Inequality and the Social Cost of Carbon,” *Journal of the Association of Environmental and Resource Economists*, March 2019, *6* (2), 29–59.
- **and Richard S.J. Tol**, “On international equity weights and national decision making on climate change,” *Journal of Environmental Economics and Management*, July 2010, *60* (1), 14–20.
- **, Cameron Hepburn, and Richard S.J. Tol**, “Equity weighting and the marginal damage costs of climate change,” *Ecological Economics*, January 2009, *68* (3), 836–849.
- Arrow, Kenneth J., Maureen L. Cropper, Christian Gollier, Ben Groom, Geoffrey M. Heal, Richard G. Newell, William D. Nordhaus, Robert S. Pindyck, William A. Pizer, Paul R. Portney, Thomas Sterner, Richard S. J. Tol, and Martin L. Weitzman**, “Should Governments Use a Declining Discount Rate in Project Analysis?,” *Review of Environmental Economics and Policy*, July 2014, *8* (2), 145–163. Publisher: The University of Chicago Press.
- Atkinson, Anthony B.**, “On the measurement of inequality,” *Journal of Economic Theory*, 1970, *2* (3), 244–263.
- Barro, Robert J.**, “Rare Disasters and Asset Markets in the Twentieth Century*,” *The Quarterly Journal of Economics*, August 2006, *121* (3), 823–866.
- **, “Rare Disasters, Asset Prices, and Welfare Costs,”** *American Economic Review*, March 2009, *99* (1), 243–264.
- Burke, Marshall, Solomon M. Hsiang, and Edward Miguel**, “Global non-linear effect of temperature on economic production,” *Nature*, November 2015, *527* (7577), 235–239.
- Dasgupta, Partha**, “Discounting climate change,” *Journal of Risk and Uncertainty*, December 2008, *37* (2), 141–169.
- Dennig, Francis, Mark B. Budolfson, Marc Fleurbaey, Asher Siebert, and Robert H. Socolow**, “Inequality, climate impacts on the future poor, and carbon prices,” *Proceedings of the National Academy of Sciences*, December 2015, *112* (52), 15827–15832.

- Dietz, Simon and Frank Venmans**, “Cumulative carbon emissions and economic policy: In search of general principles,” *Journal of Environmental Economics and Management*, July 2019, *96*, 108–129.
- , **Christian Gollier**, and **Louise Kessler**, “The climate beta,” *Journal of Environmental Economics and Management*, January 2018, *87*, 258–274.
- Diffenbaugh, Noah S. and Marshall Burke**, “Global warming has increased global economic inequality,” *Proceedings of the National Academy of Sciences*, May 2019, *116* (20), 9808–9813.
- Douenne, Thomas, Albert-Jan Hummel, and Marcelo Pedroni**, “Optimal fiscal policy in a second-best climate economy model with heterogeneous agents,” Technical Report 2022.
- Drupp, Moritz A., Mark C. Freeman, Ben Groom, and Frikk Nesje**, “Discounting Disentangled,” *American Economic Journal: Economic Policy*, November 2018, *10* (4), 109–134.
- Drupp, Moritz, Ulrike Kornek, Jasper N. Meya, and Lutz Sager**, “Inequality and the Environment: The Economics of a Two-Headed Hydra,” Working Paper 9447, CESifo Working Paper 2021.
- Duffie, Darrell and Larry G. Epstein**, “Asset Pricing with Stochastic Differential Utility,” *The Review of Financial Studies*, July 1992, *5* (3), 411–436.
- and – , “Stochastic Differential Utility,” *Econometrica*, 1992, *60* (2), 353–394. Publisher: [Wiley, Econometric Society].
- Emmerling, Johannes**, “Discounting and intragenerational equity,” *Environment and Development Economics*, February 2018, *23* (1), 19–36.
- , **Ben Groom**, and **Tanja Wettingfeld**, “Discounting and the representative median agent,” *Economics Letters*, December 2017, *161*, 78–81.
- Epstein, Larry G. and Stanley E. Zin**, “Substitution, risk aversion, and the temporal behavior of consumption and asset returns: A Theoretical Framework,” *Econometrica*, July 1989, *57* (4), 937–969.
- Fankhauser, Samuel, Richard S.J. Tol, and David W. Pearce**, “The Aggregation of Climate Change Damages: a Welfare Theoretic Approach,” *Environmental and Resource Economics*, October 1997, *10* (3), 249–266.
- Fleurbaey, Marc, Maddalena Ferranna, Mark Budolfson, Francis Dennig, Kian Mintz-Woo, Robert Socolow, Dean Spears, and Stéphane Zuber**, “The Social Cost of Carbon: Valuing Inequality, Risk, and Population for Climate Policy,” *The Monist*, 12 2018, *102* (1), 84–109.

- Freeman, Mark C, Ben Groom, Ekaterini Panopoulou, and Theologos Pantelidis**, “Declining discount rates and the Fisher Effect: Inflated past, discounted future?,” *Journal of environmental economics and management*, 2015, *73*, 32–49.
- Gollier, Christian**, “Discounting an uncertain future,” *Journal of Public Economics*, August 2002, *85* (2), 149–166.
- , “On the Underestimation of the Precautionary Effect in Discounting,” *The Geneva Risk and Insurance Review*, 2011, *36* (2), 95–111. Publisher: Palgrave Macmillan Journals.
- , *Pricing the future: The economics of discounting and sustainable development*, Princeton, NJ, USA: Princeton University Press, 2011.
- , “Discounting, inequality and economic convergence,” *Journal of Environmental Economics and Management*, January 2015, *69*, 53–61.
- , **Phoebe Koundouri, and Theologos Pantelidis**, “Declining Discount Rates: Economic Justifications and Implications for Long-Run Policy,” *Economic Policy*, 2008, *23* (56), 757–795.
- Hope, Chris**, “Discount rates, equity weights and the social cost of carbon,” *Energy Economics*, May 2008, *30* (3), 1011–1019.
- Howard, Peter H. and Thomas Sterner**, “Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates,” *Environmental and Resource Economics*, September 2017, *68* (1), 197–225.
- IAWG**, “Interagency Working Group on the Social Cost of Carbon. Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990,” Technical Report, Whitehouse, US 2021.
- Jacobs, Bas and Frederick van der Ploeg**, “Redistribution and pollution taxes with non-linear Engel curves,” *Journal of Environmental Economics and Management*, May 2019, *95*, 198–226.
- Kalkuhl, Matthias and Leonie Wenz**, “The impact of climate conditions on economic production. Evidence from a global panel of regions,” *Journal of Environmental Economics and Management*, September 2020, *103*, 102360.
- Kimball, Miles S.**, “Precautionary Saving in the Small and in the Large,” *Econometrica*, January 1990, *58* (1), 53–73.
- Klenert, David, Linus Mattauch, Emmanuel Combet, Ottmar Edenhofer, Cameron Hepburn, Ryan Rafaty, and Nicholas Stern**, “Making carbon pricing work for citizens,” *Nature Climate Change*, August 2018, *8* (8), 669–677.
- Kornek, Ulrike, David Klenert, Ottmar Edenhofer, and Marc Fleurbaey**, “The social cost of carbon and inequality: When local redistribution shapes global carbon prices,” *Journal of Environmental Economics and Management*, May 2021, *107*, 102450.

- Kotlikoff, Laurence, Felix Kubler, Andrey Polbin, Jeffrey Sachs, and Simon Scheidegger**, “Making Carbon Taxation a Generational Win Win,” *International Economic Review*, 2021, 62 (1), 3–46. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/iere.12483>.
- Kreps, David M. and Evan L. Porteus**, “Temporal Resolution of uncertainty and dynamic choice theory,” *Econometrica*, January 1978, 46 (1), 185–200.
- Lakner, Christoph and Branko Milanovic**, “Global Income Distribution: From the Fall of the Berlin Wall to the Great Recession,” *The World Bank Economic Review*, 2016, 30 (2), 203–232.
- Leland, Hayne E.**, “Saving and Uncertainty: The Precautionary Demand for Saving,” *The Quarterly Journal of Economics*, August 1968, 82 (3), 465–473.
- Matthews, H. Damon, Nathan P. Gillett, Peter A. Stott, and Kirsten Zickfeld**, “The proportionality of global warming to cumulative carbon emissions,” *Nature*, June 2009, 459 (7248), 829–832.
- Milanovic, Branko**, “Global inequality recalculated and updated: the effect of new PPP estimates on global inequality and 2005 estimates,” *The Journal of Economic Inequality*, March 2012, 10 (1), 1–18.
- , *Global Inequality: A New Approach for the Age of Globalization*, Harvard University Press, April 2016. Publication Title: Global Inequality.
- Mirrlees, James A.**, “Social benefit-cost analysis and the distribution of income,” *World Development*, February 1978, 6 (2), 131–138.
- Newell, Richard G and William A Pizer**, “Discounting the distant future: how much do uncertain rates increase valuations?,” *Journal of environmental economics and management*, 2003, 46 (1), 52–71.
- Newell, Richard G., William A. Pizer, and Brian Charles Prest**, “A Discounting Rule for the Social Cost of Carbon,” *Journal of the Association of Environmental and Resource Economists*, 2022, forthcoming (ja), null.
- Nordhaus, William**, “Estimates of the Social Cost of Carbon: Background and Results from the RICE-2011 Model,” Technical Report 17540, National Bureau of Economic Research 2011.
- , “Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches,” *Journal of the Association of Environmental and Resource Economists*, 2014, 1 (1/2), 273–312.
- Nordhaus, William D.**, “Revisiting the social cost of carbon,” *Proceedings of the National Academy of Sciences*, February 2017, 114 (7), 1518–1523.

- **and Andrew Moffat**, “A Survey of Global Impacts of Climate Change: Replication, Survey Methods, and a Statistical Analysis,” Technical Report 2017.
- Pinkovskiy, Maxim and Xavier Sala i Martin**, “Parametric Estimations of the World Distribution of Income,” Technical Report October 2009.
- Rao, Narasimha D., Petra Sauer, Matthew Gidden, and Keywan Riahi**, “Income inequality projections for the Shared Socioeconomic Pathways (SSPs),” *Futures*, January 2019, *105*, 27–39.
- Riahi, Keywan, Detlef P. van Vuuren, Elmar Kriegler, Jae Edmonds, Brian C. O’Neill, Shinichiro Fujimori, Nico Bauer, Katherine Calvin, Rob Dellink, Oliver Fricko, Wolfgang Lutz, Alexander Popp, Jesus Crespo Cuaresma, Samir KC, Marian Leimbach, Leiwen Jiang, Tom Kram, Shilpa Rao, Johannes Emmerling, Kristie Ebi, Tomoko Hasegawa, Petr Havlik, Florian Humpenöder, Lara Aleluia Da Silva, Steve Smith, Elke Stehfest, Valentina Bosetti, Jiyong Eom, David Gernaat, Toshihiko Masui, Joeri Rogelj, Jessica Strefler, Laurent Drouet, Volker Krey, Gunnar Luderer, Mathijs Harmsen, Kiyoshi Takahashi, Lavinia Baumstark, Jonathan C. Doelman, Mikiko Kainuma, Zbigniew Klimont, Giacomo Marangoni, Hermann Lotze-Campen, Michael Obersteiner, Andrzej Tabeau, and Massimo Tavoni**, “The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview,” *Global Environmental Change*, January 2017, *42*, 153–168.
- Stern, Nicholas**, *Stern Review: The Economics of Climate Change*, London: HM Treasury, 2006.
- Traeger, Christian P.**, “Recent developments in the intertemporal modeling of uncertainty,” *Annual Review of Resource Economics*, October 2009, *1* (1), 261–286.
- van der Ploeg, Frederick**, “The safe carbon budget,” *Climatic Change*, March 2018, *147* (1), 47–59.
- Vasicek, Oldrich**, “An equilibrium characterization of the term structure,” *Journal of Financial Economics*, November 1977, *5* (2), 177–188.
- Wagner, Gernot, David Anthoff, Maureen Cropper, Simon Dietz, Kenneth T. Gillingham, Ben Groom, J. Paul Kelleher, Frances C. Moore, and James H. Stock**, “Eight priorities for calculating the social cost of carbon,” *Nature*, February 2021, *590* (7847), 548–550.
- Watkiss, Paul and Chris Hope**, “Using the social cost of carbon in regulatory deliberations,” *Wiley Interdisciplinary Reviews: Climate Change*, November 2011, *2* (6), 886–901.
- Weitzman, Martin L.**, “Why the Far-Distant Future Should Be Discounted at Its Lowest Possible Rate,” *Journal of Environmental Economics and Management*, November 1998, *36* (3), 201–208.

– , “A Review of the Stern Review on the Economics of Climate Change,” *Journal of Economic Literature*, 2007, 45 (3), 703–724.

A Different quantiles of the income distribution

We can write the EDE also for any quantile of the distribution, which implicitly assumes a representative agent at a given quantile. This links one to one to the level of relative inequality aversion considered. For the lognormal distribution, the growth rate of mean income of any quantile p can be computed as

$$g_t^{(p\text{-quantile})} = \frac{1}{t}(\mu_t - \mu_0) + \frac{1}{2t}(\sigma_t^2 - \sigma_0^2)\phi^{(-1)}(p\text{-quantile}) \quad (\text{A.1})$$

where Φ^{-1} denotes the inverse of the cumulative distribution function of the standard normal distribution.

This formula shows how for each chosen quantile and degree of relative intragenerational inequality aversion the growth rate of the EDE level of consumption can be computed. That is, each level of intragenerational inequality aversion implies an EDE growth rate that reflects a particular quantile of the income distribution. To answer which quantiles are the relevant ones to consider for a given level of relative intragenerational inequality aversion, we note that if $\phi^{-1}(p\text{-quantile}) = 1 - \eta$ holds, the given quantile growth rate and EDE growth rate coincide. Hence, $p\text{-quantile} = \phi(1 - \eta)$ gives the quantile for a decision maker with relative intragenerational inequality aversion of η , which can be considered as the representative agent, see also the application to country level growth rates in Turk et al. (2020). For $\eta = 1$ (logarithmic utility), the quantile is just 0.5 or the median. For $\eta = 2$, this corresponds to the 15% quantile, and for $\eta = 4$ it corresponds to the 0.1%th quantile. This shows how strongly relative intragenerational inequality aversion impacts which quantile corresponds to EDE income. For $\eta = 0$, we have inequality-neutral growth which corresponds to the 84%th quantile. This reflects that higher growth of higher incomes contributes more to average per-capita growth. We can use this for empirical purposes but also to compute the desired SCC for different quantiles.

B The case where income and impacts are correlated

In the main part of our paper, we have considered marginal impacts from climate change of unity across the full income distribution. This can be generalised to allow for any distribution of impacts and notably allowing for correlation with the income of citizens. The latter is important given that evidence is emerging that climate impacts affect poor countries more negatively than rich countries (Diffenbaugh and Burke, 2019), while within countries evidence is less conclusive.

Now suppose that consumption is equal to income minus impacts or damages ($c = y(1-d)$) and as before consumption is lognormally distributed. First, note that if damages are uncorrelated with income, due to the (reasonable) multiplicative specification, the results are identical to the constant damage used in the main text. In particular, we know that then the growth of EDE consumption, which determines the wealth effect in the calculation of the SDR, is equal to

$$g_t^{EDE} = g^{mean} + \eta (g^{median} - g^{mean}) = g^{mean} - 0.5\eta\Delta\sigma_c^2 \quad (\text{A.2})$$

Now instead if we assume that $(1-d)$ and income, y , are jointly bivariate lognormally distributed with correlation coefficient ρ , so that d and y are correlated as $\rho_{yd} = -\rho$. Then due to the laws for a product of two bivariate lognormal variables, we have

$$\begin{aligned} g_t^{EDE} &= (g^{y,mean} - g^{d,mean}) - 0.5\eta [\Delta\sigma_y^2 + \Delta\sigma_d^2 - 2\rho_{yd}\Delta\sigma_y\Delta\sigma_d] \\ &= g_{\rho_{yd}=0}^{EDE} + \eta\rho_{yd}\Delta\sigma_y\Delta\sigma_d. \end{aligned} \quad (\text{A.3})$$

Compared to the situation where damages are uncorrelated to income (where $g^{EDE} = g_{\rho_{yd}=0}^{EDE}$), now if the rich are hit more severely than the poor ($\rho_{yd} > 0$), g^{EDE} is increased because inequality is reduced (high incomes are attenuated compared to lower incomes).¹¹ The opposite is true when the poor are hit more strongly than the rich, i.e., if $\rho_{yd} < 0$. Since g^{EDE} determines the social discount rate and hence the social cost of carbon through equations (7) and (15) monotonically, the comparatives are straightforward: an increase in the correlation leads to a higher SDR and SCC, and vice versa. Under different distributional assumptions, or the individual approach, or adding uncertainty, these results will however change, and we leave this for future research. Yet, this first

¹¹This assumes that $\Delta\sigma_d > 0$, which is trivially the case as climate damages are higher in the future.

result indicates that in climate damages that are regressive indicate an optimal carbon price that is higher ceteris paribus.

C Derivation of equation (28) for the social discount rate under uncertainty

Let us first abstract from intragenerational inequality and inequality aversion, so c_t refers to consumption of the representative consumer or mean consumption at time t . Welfare is given by the recursive formulation:

$$W_t \equiv E_t \left[\int_t^\infty f(c_s, W_s) ds \right] \quad (\text{A.4})$$

with $f(c, W) = \delta \theta W \left[\frac{c^{1-\omega}}{[(1-\gamma)W]^{1/\theta}} - 1 \right]$ if $\omega \neq 1$ and $W = (1-\gamma)W \ln \left(\frac{c}{[(1-\gamma)W]^{1/(1-\gamma)}} \right)$ if $\omega = 1$, where $\theta \equiv \frac{1-\gamma}{1-\omega}$ (Duffie and Epstein, 1992).

Assume that mean consumption follows a geometric Brownian motion with jumps:

$$dc = \vartheta c dt + \nu c dW - l c dJ, \quad (\text{A.5})$$

where W is a standard Wiener process, ϑ denotes the drift and ν the volatility of the geometric Brownian motion, and J is a jump process with (downward) jump size $l \in (0, 1)$ (as fraction of consumption) and intensity λ . Let the remaining fraction after a jump, $Z \equiv 1 - l$, have a power distribution $f(Z) = \alpha Z^{\alpha-1}$ with $\alpha > 0$ defined on the interval $Z \in (0, 1)$, so that $E[Z^n] = \frac{\alpha}{\alpha+n}$.

With temperature a linear function of cumulative emissions, and the damage ratio linear in temperature, marginal damages from global warming are proportional to aggregate consumption and temperature, i.e., $\chi_1 \zeta_1 N c$, where N denotes the number of households in the economy, ζ_1 the transient climate response to cumulative emissions, and χ_1 the damage coefficient (the marginal effect of temperature on the damage ratio). Under these assumptions we have the following proposition.

Proposition C.1: The social cost of carbon is given by

$$SCC_t = \frac{\chi_1 \zeta_1}{R} N c_t, \quad (\text{A.6})$$

where the discount rate used to calculate the SCC is constant and given by

$$R = \delta + (\omega - 1) \left(\vartheta - \frac{1}{2} \gamma \nu^2 \right) + \lambda E \left[1 - Z^{-\gamma} + \frac{\gamma - \omega}{\gamma - 1} (Z^{1-\gamma} - 1) \right]. \quad (\text{A.7})$$

or $R = \delta + (\omega - 1) \left(\vartheta - \frac{1}{2} \gamma \nu^2 \right) + \lambda \left(-\frac{\gamma}{\alpha - \gamma} + \frac{\gamma - \omega}{\alpha + 1 - \gamma} \right)$. To allow for intragenerational inequality aversion, replace ϑ in equation (A.7) by $\vartheta - \eta h$.

Proof: The value function $W = W(C)$ gives welfare to go for the problem of maximising (A.4) subject to (A.5) and can be solved from the Hamilton-Jacobi-Bellman equation

$$0 = f(c, W(c)) + W'(c) c \vartheta + \frac{1}{2} W''(c) c^2 \nu^2 + \lambda E [W(Zc) - W(c)] \quad (\text{A.8})$$

Conjecture that the value function has the form $W(c) = \frac{(Xc)^{1-\gamma}}{1-\gamma}$, so $W'(c) = X^{1-\gamma} c^{-\gamma}$ and $W''(c) = -\gamma X^{1-\gamma} c^{-\gamma-1}$. Upon substitution into equation (A.8) and dividing by $(Xc)^{1-\gamma}$, we obtain

$$0 = \frac{\delta}{1-\omega} (X^{\omega-1} - 1) + \vartheta - \frac{1}{2} \gamma \nu^2 + \frac{\lambda}{1-\gamma} (E [Z^{1-\gamma}] - 1). \quad (\text{A.9})$$

This can be solved for the constant

$$X = \left[1 - \frac{1-\omega}{\delta} \left\{ \vartheta - \frac{1}{2} \gamma \nu^2 + \frac{\lambda}{1-\gamma} (E [Z^{1-\gamma}] - 1) \right\} \right]^{\frac{1}{\omega-1}}. \quad (\text{A.10})$$

Duffie and Epstein (1992) show that the SDF for this specification of recursive utility is

$$H_t = \exp \left(\int_0^t f_W(c_s, W_s) ds \right) f_c(c_t, W_t), \quad (\text{A.11})$$

where equation (A.11) implies that the SDF satisfies

$$\frac{dH}{H_-} = \frac{df_c(c_-, W)}{f_c(c_-, W)} + f_W(c, W) dt. \quad (\text{A.12})$$

From equation (A.4), $f_C = \frac{\delta c^{-\omega}}{[(1-\gamma)W]^{\frac{1}{\theta}-1}} = \delta c^{-\gamma} X^{\omega-\gamma} \equiv g(c)$. Ito's lemma gives $df_c(c, W) = dg(c) = g'(c)dc^c + \frac{1}{2}g''(c)c^2\nu^2dt + (g((1-l)c) - g(c))dJ$, where c^c indicates the continuous part of the process for c (ignoring jumps), so that $\frac{dg(c)}{g(c_-)} = -\gamma(\vartheta dt + \nu dW) + \frac{1}{2}\gamma(1+\gamma)\nu^2dt + [Z^{-\gamma} - 1]dJ$. Using these two relationships, equation (A.12) gives

$$\frac{dH}{H} = f_W dt - \gamma (\vartheta dt + \nu dW) + \frac{1}{2} \gamma (\gamma + 1) \nu^2 dt + [Z^{-\gamma} - 1] dJ \quad (\text{A.13})$$

where using $\theta - 1 = \frac{\omega - \gamma}{1 - \omega}$ and the value function with X from equation (A.10) yields

$$\begin{aligned} f_W &= \\ &\delta (\theta - 1) c^{1-\omega} [(1 - \gamma) W]^{-\frac{1}{\theta}} - \delta \theta = \delta (\theta - 1) X^{\omega-1} - \delta \theta \\ &= -\delta - (\omega - \gamma) \left\{ \vartheta - \frac{1}{2} \gamma \nu^2 + \frac{\lambda}{1 - \gamma} (E [Z^{1-\gamma}] - 1) \right\}. \end{aligned} \quad (\text{A.14})$$

In equilibrium, the risk-free discount rate equals *minus* the expected rate of change of the SDF, so that (using equations (A.12) and (A.13) and $E [dW] = 0$) we have

$$r_F = \delta + \omega \vartheta + (\omega - \gamma) \left[-\frac{1}{2} \gamma \nu^2 + \frac{\lambda}{1 - \gamma} (E [Z^{1-\gamma}] - 1) \right] - \frac{1}{2} \gamma (\gamma + 1) \nu^2 - \lambda E [Z^{-\gamma} - 1]. \quad (\text{A.15})$$

Collecting terms, we obtain

$$r_F = \delta + \omega \vartheta - \frac{1}{2} (1 + \omega) \gamma \nu^2 - \lambda E \left[Z^{-\gamma} - 1 + \frac{\omega - \gamma}{\gamma - 1} (Z^{1-\gamma} - 1) \right]. \quad (\text{A.16})$$

Note that the term structure for the safe rate is flat. The SCC is obtained from

$$SCC_t = E \left[\int_t^\infty \chi_1 \zeta_1 H_{s-t} N c_{s-t} ds \right] = \chi_1 \zeta_1 N E \left[\int_t^\infty G_{s-t} ds \right], \quad (\text{A.17})$$

where $G \equiv Hc$. Note that $dc = dc^c - lcdJ$. Combining equations (A.13) and (A.5) and using Ito's lemma, we obtain

$$\begin{aligned} \frac{dG}{G_-} &= \frac{dH}{H_-} + \frac{dc}{c_-} + \frac{d\langle H, c \rangle}{Hc} = f_W dt + (1 - \gamma) (\vartheta dt + \nu dW) \\ &\quad + \frac{1}{2} \gamma (\gamma + 1) \nu^2 dt + [Z^{-\gamma} - 1] dJ + \frac{d\langle H, c \rangle}{Hc}, \end{aligned} \quad (\text{A.18})$$

where $\langle H, c \rangle_t = \frac{1}{2} (\langle H + c \rangle_t - \langle H \rangle_t - \langle c \rangle_t)$ are the covariances or cross-covariances of the stochastic processes H and c , and $\langle c \rangle_t, \langle H \rangle_t$ and $\langle H + c \rangle_t$ are the quadratic variations of the processes c , H and $H + c$ (all of the continuous parts only). Using $(dW_t)^2 \sim N(0, dt)$ and ignoring terms such as $dt dW$ and $(dt)^2$, $d\langle c \rangle_t \equiv (dc_t)^2 = \nu^2 dt$, $d\langle H \rangle_t = \gamma^2 \nu^2 H dt$, $d\langle H + c \rangle_t = (c - \gamma H)^2 \nu^2 dt$, and thus $\frac{d\langle H, c \rangle}{Hc} = -\gamma \nu^2 dt$. Substituting this and expression (A.14) into equation (A.18) and taking expectations gives the risk-adjusted discount rate

used to calculate the SCC, R , as minus the expected rate of change of G , i.e.,

$$R = \delta + (\omega - 1) \left(\vartheta - \frac{1}{2} \gamma \nu^2 \right) - \lambda E \left[Z^{-\gamma} - 1 + \frac{\omega - \gamma}{\gamma - 1} (Z^{1-\gamma} - 1) \right]. \quad (\text{A.19})$$

The sum of the prudence term, $-\frac{1}{2}(1 + \omega)\gamma\nu^2$, and the risk premium, $\gamma\nu^2$, gives the term $-(\omega - 1)\frac{1}{2}\gamma\nu^2$ in equation (A.19). Equation (A.19) corresponds to equation (A.7) of Proposition C.1. Equations (A.16) and (A.19) give the difference between the discount rate used to calculate the SCC, R and the safe rate as $\pi = R - r_F = \gamma\nu^2 - \vartheta$. The term $\gamma\nu^2$ is the premium for GBM risk, and $-\vartheta$ corrects for expected growth in the economy and marginal damages. The SCC is obtained by substituting (A.19) into (A.17). ■

Note that the safe rate (A.16) corresponds to Hambel (2021, equation (6.3)) (without temperature interaction risk). Various special cases of the discount rate (A.19) have been used in the literature. Golosov et al. (2014) have no jumps and logarithmic utility, ($\omega = \eta = 1$), so use $R = \delta$. Van den Bremer and van der Ploeg (2021) have no jumps but allow for recursive utility, so obtain $R = \delta + (\omega - 1)(\vartheta - \frac{1}{2}\gamma\nu^2)$ (setting their 0th-order growth rate to ϑ) in line with equation (A.19).

To allow for intragenerational inequality, suppose that the drift of EDE consumption is not given by θ but by $\theta - \eta h$, where η denotes the coefficient of relative intragenerational inequality aversion and h the difference between the mean and median drift. We suppose that intragenerational inequality does not affect macroeconomic volatility of the jump processes. EDE consumption thus follows a geometric Brownian motion with jumps $dc^{EDE} = (\theta - \eta h)c dt + \nu c dW - l c dJ$. The SCC is thus given by Proposition 3.

To allow for a climate β , suppose that global warming damages are proportional to $C = c^\beta$ rather than to c . The safe rate is unaffected but the SCC is now obtained from

$$SCC_t = E \left[\int_t^\infty \chi_1 \zeta_1 H_{s-t} N c_{s-t}^\beta \right] = \chi_1 \zeta_1 N E \left[\int_t^\infty G_{s-t} ds \right], \quad (\text{A.20})$$

where $G \equiv HC = Hc^\beta$. Using the same procedure as before, we obtain the discount rate, R given in equation (30) and the SCC given in equation (31).

D The SCC with the individual approach

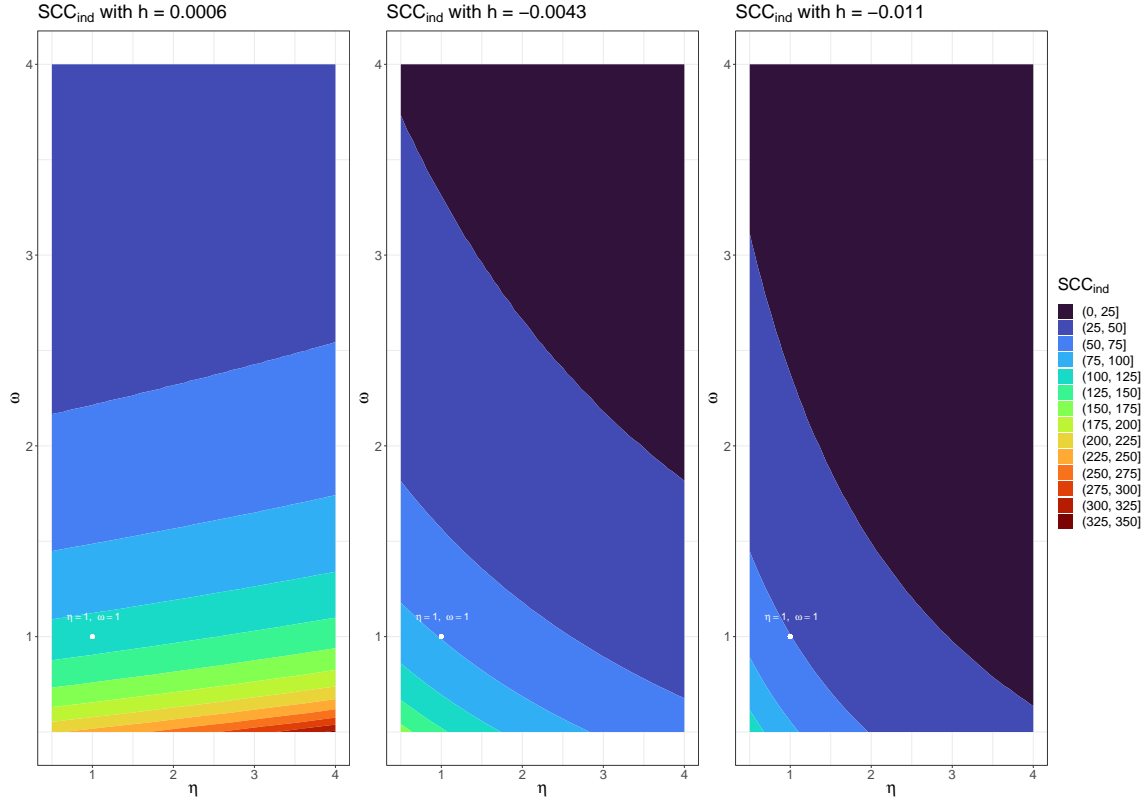


Figure 5: The SCC as function of intragenerational (η) and intergenerational inequality aversion (ω), deterministic approach. The figure shows how the SCC from equation (17), the *individual* approach, varies with η and ω . SSP4 has inequality-increasing growth and is approximated by $h = 0.006$. SSP2 has inequality-decreasing growth and is approximated by $h = -0.0043$. SSP1 has sharply inequality-decreasing growth and is approximated by $h = -0.011$.