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The Social Cost of Carbon with Intragenerational Inequality and Economic Uncertainty*

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Abstract

An analytical formula is presented for the Social Cost of Carbon (SCC) taking account of intragenerational income inequality, in addition to intergenerational income inequality, macro-economic uncertainty and rare disasters to economic growth. The social discount rate is adjusted for intra- and intergenerational inequality aversion and risk aversion. If growth reduces intragenerational inequality, the SCC is lower than with inequality-neutral growth, especially if intra- and intergenerational inequality aversion are high. Calibrated to the observed interest rate and risk premium, the SCC in 2020 is $\$125/tCO_2$ without considering intragenerational inequality, $\$81/tCO_2$ if intragenerational inequality decreases over time, as a continuation of historical trends suggests (based on Shared Socioeconomic Pathway (SSP) 2), and $\$213/tCO_2$ if inequality increases (SSP4). Intragenerational inequality has a similar order of effect on the SCC as accounting for rare macroeconomic disasters.

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

JEL codes: C61, D31, D62, D81, G12, H23, Q54

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1 Introduction

The Social Cost of Carbon (SCC): the discounted present value of future damages from the marginal ton of carbon emitted, aims to reflect the long-term intertemporal welfare implications of today's carbon emissions. Consequently, the SCC is particularly sensitive to the Social Discount Rate (SDR). Yet, current estimates of the SCC and the SDR used in policy ignore many factors that determine welfare in the context of climate change (Wagner et al., 2021) leading to calls in policy circles to provide more scientific assessments of the SCC and clearer guidance on the SDR. (Aldy et al., 2021). Perhaps chief among the omitted factors is a treatment of *intra*- rather than *inter*generational inequality. While general recommendations exist for accounting for the distributional effects of environmental policy in appraisal (e.g., Drupp et al., 2021), evidence from Integrated (climate-economy) Assessment Models shows that intragenerational inequality aversion might be an important determinant of the SCC (Dennig et al., 2015; Anthoff and Emmerling, 2019). In particular because the classical Kaldor-Hicks argument: that winners could compensate losers in a cost-benefit framework, might not applicable in the global and long-term context of climate change (Stern, 2016).

From a practical perspective, in the United States, Executive Order 13990 specifically requires inequality to be considered in the assessment of the economic impacts of air pollutants and emissions including CO2 (IAWG, 2021). There is a clear need, therefore, 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. Recently, Rennert et al. (2022) have updated existing estimates of the SCC and find a mean a value of $187 per ton of CO2 without considering intragenerational inequality.

Our analysis makes the following three innovations. First, we extend earlier results on the effects of secular changes in intragenerational inequality on the SDR (Gollier, 2015; Emmerling, 2018), by deriving an analytical formula for the resulting SCC. Our rule for the SCC is tractable, can be easily interpreted, and complements earlier numerical results on the effect of inequality on the SCC (Anthoff and Emmerling, 2019).

Second, we extend our analytical rule for the SCC to allow for regular macroeconomic uncertainty and for the risk of rare macroeconomic disasters. Third, we perform a careful analysis of within-country inequality and how this changes over time based on calibrated scenarios on the development of global inequality. We then show quantitatively how this calibration affects the SCC.

We address these important policy issues by adjusting the Keynes-Ramsey rule for the SDR to take account of both intra- and intergenerational inequality aversion and the evolution of inequality over time. We correct for the fact that the standard approach ignores aversion to intragenerational income inequalities (cf. 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.[1]

We model the dynamics of the intragenerational income distribution with a lognormal income distribution (e.g., Pinkovskiy and Sala-i Martin, 2009).[2] We also allow the distributions to become over time more unequal, less unequal, or stay the same as the economy grows. We capture this 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 the following assumptions. First, global warming damages as fraction of world economic activity are roughly linear in temperature (Burke et al., 2015; Kalkuhl and Wenz, 2020). Second, temperature is driven by cumulative emissions (e.g., Matthews et al., 2009; van der Ploeg, 2018; Dietz and Venmans, 2019). Third, global mean consumption growth is given by a geometric Brownian motion complemented with risks of rare macroeconomic disasters (e.g., Barro, 2009; Barro and Jin, 2011). Fourth,

[1]We also refer to the latter as intergenerational inequality aversion. This is not quite correct, since strictly speaking we do not allow for different generations but do consider different households at different points of time.

[2]For reasons of analytical tractability, we abstract from a Pareto tail in the income distribution for the top incomes.

as already mentioned, inequality in consumption levels across agents at a particular point of time is represented by a lognormal distribution. Finally, preferences of policy makers are described by their aversion to risk, aversion to intergenerational inequality, aversion to intragenerational inequality, and their impatience.

Armed with these assumptions, we show analytically 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 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).

When we calibrate our model to the observed safe interest rate and macroeconomic risk premium and consider a scenario where global intragenerational inequality falls moderately with economic growth, the usual SCC of $125/tCO2$ (in 2020 US dollars) for 2020 drops to \$$81/tCO2$ if account is taken of intragenerational inequality. Accounting for inequality and inequality aversion has a significant effect on the SCC, similar in magnitude to accounting for rare macroeconomic disaster risk.

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 benchmark model and discusses the sensitivity of various parameters. 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 (Riahi et al., 2017). Section 9 discusses the effects of different correlations between impacts of global warming damages and income on the SCC. Section 10 concludes.

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 $U\left(c_t(\theta)\right)$, where $c_t(\theta)$ denotes 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 $U\left(c_t(\theta)\right) = \left(c_t(\theta)^{1-\eta^{-1}}\right)/(1-\eta)$ if $\eta \neq 1$ and $U\left(c_t(\theta)\right) = \ln c_t(\theta)$ if $\eta = 1$. The elasticity $\eta = -c_t U''\left(c_t(\theta)\right)/U'\left(c_t(\theta)\right) > 0$ 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 the level of consumption that, if everyone in society received it, gives the same felicity as the actual distribution of consumption levels (Atkinson, 1970). The level of EDE consumption can be written as $c_t^{EDE} = U^{-1}\left(\int_\theta U\left(c_t(\theta)\right) dF(\theta)\right)$. 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".

Assuming 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

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

Without intragenerational inequality aversion ($\eta = 0$), EDE consumption equals mean consumption $c_t^{mean} = \exp\left(\mu_t + {\sigma_t}^2/2\right)$. 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 (η) and higher intragenerational inequality in consumption levels (higher σ_t) 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 $0 \leq I_t(\eta) = 1 - \exp\left(-\eta{\sigma_t}^2/2\right) < 1$. Dispersion in lognormally distributed consumption drives median consumption below mean consumption. The standard deviation of consumption at time t is $\exp\left(\mu_t + {\sigma_t}^2/2\right)\sqrt{\exp({\sigma_t}^2) - 1}$ and the corresponding coefficient of variation is $\sqrt{\exp({\sigma_t}^2) - 1}$. Each is directly related to the Atkinson Index. Finally, the annualised growth rate of EDE consumption is defined as $g_t^{EDE} \equiv \ln(c_t^{EDE}/c_0^{EDE})/t$ and equals

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

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

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

(cf. Emmerling et al., 2017).[3] 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

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

For the Atkinson index of inequality, this implies $I(\eta) = 1 - e^{-\frac{\eta}{2}}(\sigma_0^2 + 2ht)$. 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

[3]Instead 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).

time t is now $\sqrt{\exp({\sigma_0}^2 + 2ht) - 1}$ and rises with time if $h > 0$.[4] 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 $V(c^{EDE}) = \left((c^{EDE})^{\omega-1} - 1\right)/(1-\omega)$ 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 same rate of time impatience or pure time preference $\delta > 0$. Within the expected utility framework, utilitarian social welfare is given by

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

This welfare function generalises Gollier (2015) by separating out the coefficients of relative intragenerational and intergenerational inequality aversion (η and ω, respectively). This is important for the integrated assessment of climate policy (e.g., 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 also abstract from uncertainty (where the distinction does not matter) and use the welfare function $W_0 = \int_0^\infty e^{-\delta t} V({c_t}^{EDE})dt$.

Appendix B considers an alternative "individual" approach for the marginal evaluation of consumption which differs in the way marginal changes in consumption are distributed in the economy. It thus considers the inequality effect in the baseline over

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

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. This contrasts with our chosen approach with 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.[5] Whereas in the EDE approach policy-makers first take a stance on inequality aversion at a particular point of time, and then compare welfare of the EDE individual over time, the *individual* approach takes into account individual changes in marginal utility arising from the marginal costs and benefits of the project. We have chosen to focus at the EDE approach because we believe it is simpler to communicate to policy makers. However, we will also report calculations for the SDR and the SCC with the *individual* approach.

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 thus defined as

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

We use 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)[6]

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

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

$$r_t = \delta + \omega(g_t - \eta h). \tag{8}$$

[5] With the individual approach, 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. In contrast, the EDE approach considers 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}. The *EDE* approach is equivalent to Emmerling et al. (2017) while the *individual* approach is as in Gollier (2015).

[6] The EDE approach simplifies inclusion of intragenerational equality considerably. In Appendix B we discuss the *individual* approach, where inequality in the marginal effect of the project is also considered.

The adjustment for intragenerational inequality aversion is thus $\omega\eta(g_t^{median} - g_t^{mean})$.[7]

The conventional Ramsey rule gives the unadjusted SDR as $r_t^U = \delta + \omega g_t{}^{mean} = \delta + \omega g$, where $\omega g_t{}^{mean} = \omega g_t$ 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., $g_t^{EDE} - g_t^{mean} = -h$, (ii) intragenerational inequality aversion, η; and (iii) the coefficient of relative intergenerational inequality aversion, ω, which together give $-\omega\eta h$.

Higher EDE growth implies that future generations are richer than current generations in terms of EDE consumption, 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 (simple Ramsey Rule) 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, policy-makers find the future more important relative to the present if intragenerational inequality rises over time, and the gap between mean and EDE consumption rises. 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 more unequal societies. Conversely, if economic growth is associated with falling intragenerational inequality ($h < 0$), the SDR 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. In section 6 we extend the analysis to uncertainty

[7]Emmerling 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 = 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 = = 2 but by roughly 0.25 percentage points if = = 1. For the Netherlands, this effect increases the SDR by 0.6%- and 0.2%-point, respectively.

about the rate of economic growth and obtain a generalised expression for the SDR (and for the SCC) that also separates out society's attitude to risk aversion

5 The inequality-adjusted social cost of carbon

The SCC is the (expected) 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 resulting increases in temperature. Before we can derive the SCC, we specify our model of damages and temperature.

5.1 Drivers of global warming damages

Let D_t denote global warming damages, T_t denote temperature measured relative to its preindustrial level, and E_t denote cumulative emissions, all at time t. For simplicity, we abstract from population growth and denote the number of agents in the economy by the constant N. Furthermore, we assume that global warming damages are proportional to aggregate economic activity (here aggregate consumption) and linear in temperature increases, so that

$$D_t = (\chi_0 + \chi_1 T_t) N {c_t}^{mean}. \tag{9}$$

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

5.2 Temperature and cumulative emissions

Temperature is driven by cumulative emissions, so that

$$T_t = \xi_0 + \xi_1 E_t \text{ with } E_t = \int_0^t e_s ds. \tag{10}$$

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 is thus $\chi_1 \xi_1 N {c_t}^{mean}$. To evaluate this marginal effect in monetary terms today, we will specify a welfare function according to the *EDE* (and Appendix D reconsiders the analysis for the *individual* approach).

5.3 The social cost of carbon under the EDE 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 and the denominator is the marginal contribution to welfare of initial global consumption (to ensure that the SCC is measured in units of consumption goods or dollars). The SCC is thus defined by

$$SCC_0 \equiv \frac{N \int_0^{\infty} e^{-\delta t} \left(\frac{\partial D_t}{\partial T_t}\right) \left(\frac{\partial T_t}{\partial E_t}\right) \left(\frac{\partial E_t}{\partial e_0}\right) \frac{\partial W_0}{\partial c_t} dt}{\partial W_0 / \partial c_0}. \tag{11}$$

This allows us to derive the SCC for different social welfare functions and their respective SDR. With global warming damages and temperature change defined as above and making use of the fact that under our assumptions the term structure of the discount rate is flat, the SCC becomes

$$SCC_0 = \frac{\chi_1 \xi_1 N {c_0}^{mean}}{R}, \tag{12}$$

where $R \equiv r_t - g$ denotes the constant growth-corrected social discount rate used to calculate the SCC. 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 rise in line with the rate of growth aggregate consumption.

The EDE approach based on the welfare function given by equation (5) gives the SCC by deriving by the marginal impact on the welfare of the EDE agent today, i.e.,

$$SCC_0 \equiv \frac{N \int_0^{\infty} e^{-\delta t} \left(\frac{\partial D_t}{\partial T_t}\right) \left(\frac{\partial T_t}{\partial E_t}\right) \left(\frac{\partial E_t}{\partial e_0}\right) V'({c_t}^{EDE}) dt}{V'({c_0}^{EDE})}. \tag{13}$$

Proposition 1. *In the absence of uncertainty, the initial social cost of carbon under the EDE approach is*

$$SCC_0 = \left(\frac{\chi_1 \xi_1}{\delta + (\omega - 1)g - \omega \eta h} \right) N {c_0}^{mean}, \tag{14}$$

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 intragenerational inequality aversion, h the difference between the growth of mean income and the growth of median income, χ_1 the increase in the damage ratio per degree Celsius of global warming, ξ_1 the transient climate response to cumulative emissions, and $N{c_0}^{mean}$ initial aggregate consumption.

Proof. Substituting relationships (9) and (10) into (13) and using (4), we obtain

$$SCC_0 = N \int_0^\infty e^{-\delta t} \chi_1 {c_t}^{mean} \xi_1 \left(\frac{{c_t}^{EDE}}{{c_0}^{EDE}} \right)^{-\omega} dt, \tag{15}$$

which simplifies to equation (14).

□

The denominator in the parentheses in the expression for the SCC given in equation (14) 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 (14) 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 ($r_t^U - g$ with $r_t^U = \delta + \omega g$). Higher impatience ($\delta$) 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 as rising intergenerational inequality (due to $g > 0$), the SDR in (7) is reduced and the SCC in equation (14) is increased. This effect is stronger 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 so that the SDR is increased and the SCC 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 (decreasing) growth increases (decreases) 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.[8]

6 SCC with intra- and intergenerational inequality and economic uncertainty

The EDE approach stems from an intuitive social welfare function (see equation (5)) and provides a simple and natural framework within which to introduce uncertainty and catastrophic impacts. Here we extend this approach by allowing for uncertainty in the development of per-capita (mean) consumption. We introduce uncertainty about future economic growth prospects by assuming that the stochastic process for mean consumption is given by geometric Brownian motion with drift. Hence,

$$dc_t^{mean} = \vartheta c_t^{mean} dt + \upsilon c_t^{mean} d_t, \tag{16}$$

where ϑ denotes the drift, υ denotes the volatility, and Z_t is a unit Wiener process. The stochastic process (16) has the solution $c_s^{mean} = c_t^{mean} \exp\left((\vartheta - \upsilon^2/2)(s-t) + \upsilon Z_s\right)$.

[8]On the other hand, the individual approach described in Appendix B 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). This is another reason why we prefer the EDE approach to the *individual* approach.

where the expected value of future consumption equals $\mathrm{E}_t\left[c_s^{mean}\right]=e^{\vartheta(s-t)}c_t^{mean}$ with time-varying variance $var(c_s^{mean})=e^{2\vartheta(s-t)}(e^{\upsilon^2(s-t)}-1)(c_t^{mean})^2,\ s\geq t$. Furthermore, we have $\mathrm{E}_t\left(\ln c_s^{mean}/\ln c_t^{mean}\right)=(\vartheta-\upsilon^2/2)(s-t)$.

To allow for a coefficient of relative *risk* aversion, γ, that is separate from the coefficient of relative *intergenerational* inequality aversion, ω, we adopt recursive preferences (e.g., Kreps and Porteus, 1978; Epstein and Zin, 1989; Duffie and Epstein, 1992a,b). The social welfare function is then no longer given by the expected utility specification (5), but by the recursive formulation

$$W_t=\mathrm{E}_t\left[\int_t^\infty f(c_s^{EDE},W_s)ds\right]\ \text{ with }\ f(c_t^{EDE},W_t)=\delta\theta W\left[\frac{(c_t^{EDE})^{1-\omega}}{((1-\gamma)W_t))^{\frac{1}{\theta}}}-1\right]. \tag{17}$$

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 the inverse of the elasticity of intertemporal substitution) as before and γ the coefficient of relative risk aversion. Instead of using the growth-corrected interest rate $R=r_t-g_t$ with r_t the deterministic SDR given by equation (8) and $g_t^{EDE}=\vartheta-\eta h$, Appendix C shows that the discount rate used to calculate the SCC now equals

$$\begin{aligned}R=&\underbrace{\delta}_{\text{impatience}}+\underbrace{\omega\vartheta}_{\text{affluence}}-\underbrace{\omega\eta h}_{\text{rising inequality}}-\underbrace{\vartheta}_{\text{rising damages}}\underbrace{-\frac{1}{2}(1+\omega)\gamma\upsilon^2}_{\text{prudence}}+\underbrace{\gamma\upsilon^2}_{\text{insurance}}\\&=\delta+(\omega-1)\left(\vartheta-\frac{1}{2}\gamma\upsilon^2\right)-\omega\eta h.\end{aligned} \tag{18}$$

This decomposition of the expression for the discount rate in equation (18) is the same as in van den Bremer and van der Ploeg (2021), except that there is now an additional correction term $-\omega\eta h$ to allow for rising intragenerational inequality aversion.

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.[9] Combining the prudence and insurance terms in the expression for the SDR gives $-\frac{1}{2}(\omega-1)\gamma\nu^2$, so that the prudence term dominates the insurance term if $\omega > 1$ holds.

The SCC corresponding to the discount rate (18) is given by

$$SCC_0 = \left(\frac{\chi_1 \xi_1}{\delta + (\omega - 1)(\vartheta - \gamma\upsilon^2/2) - \omega\eta h} \right) N c_0{}^{mean}, \tag{19}$$

where the denominator is the return on risky assets minus the rate of economic growth, i.e., $R = r_t - \vartheta$, to allow for damages growing in line with economic activity. If intergenerational inequality aversion and the elasticity of intertemporal subtitution equal one (i.e., $\omega = 1$), there is no effect of macroeconomic uncertainty on the SCC because $SCC_0 = \left(\frac{\chi_1\xi_1}{\delta-\eta h}\right) N c_0{}^{mean}$. Equation (19) can be extended in two directions.

6.1 Extension: the climate beta

The first extension 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 $\beta = 1$. The case where damages are unrelated to aggregate economic activity ("additive" damages) corresponds to $\beta = 0$. For general climate beta β, the discount rate given in equation (18) becomes

$$R = \delta + (\omega - \beta)(\vartheta - \tfrac{1}{2}\gamma\upsilon^2) - \tfrac{1}{2}(1 - \beta)(\gamma - \beta)\upsilon^2 - \omega\eta h \tag{20}$$

(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.[10] The SCC corresponding to

[9]Without the rising inequality and insurance terms, the SDR becomes $r_t = \delta + \omega\vartheta - \omega\upsilon^2/2$ 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).

[10]The 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.

equation (20) becomes

$$SCC_0 = \left(\frac{\chi_1 \xi_1}{\delta + (\omega - \beta)(\vartheta - \frac{1}{2}\gamma \upsilon^2) - \frac{1}{2}(1-\beta)(\gamma - \beta)\upsilon^2 - \omega \eta h} \right) N {c_0}^{mean}, \tag{21}$$

where the denominator of this expression equals R (see Appendix C). If $\beta = 1$, equation (21) collapses to equation (19). If damages are less than proportional to economic activity, i.e., $\beta < 1$, the denominator R is higher and the SCC is lower than if $\beta = 1$ provided $\vartheta - \eta h > \gamma \upsilon^2$. 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.

6.2 Risk of rare macroeconomic disasters

The second extension of equation (19) 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 $\phi \equiv 1 - l$. The generalised expression for the discount rate used to calculate the SDR given in equation (18) becomes

$$R = \delta + (\omega - 1)\left(\vartheta - \frac{1}{2}\gamma \upsilon^2 - \frac{\lambda}{1-\gamma}\left(1 - \mathrm{E}[\phi^{1-\gamma}]\right) \right) - \omega \eta h \tag{22}$$

(see Appendix C). We assume that the recovery fraction has a power distribution with density function $\alpha \phi^{\alpha - 1}$ defined on the interval $\phi \in (0, 1)$ with $\alpha > 0$.

6.3 General result

Proposition 2. *The initial SCC under the EDE approach adjusted for both inequality and for normal and rare disaster risks in the rate of economic growth with a general elasticity of global warming damages with respect to aggregate consumption, β, equals*

$$SCC_0 = \frac{\chi_1 \xi_1 N {c_t}^{mean}}{R} \tag{23}$$

with

$$
\begin{aligned}
R = {} & \delta + (\omega - \beta)(\vartheta - \frac{1}{2}\gamma\upsilon^2) - \frac{1}{2}(1-\beta)(\gamma-\beta)\upsilon^2 - \omega\eta h \\
& + \lambda\left(\frac{\omega-1}{\gamma-1}\right)\left(1 - \mathrm{E}[\phi^{1-\gamma}]\right) + \lambda\mathrm{E}[\phi^{1-\gamma} - \phi^{\beta-\gamma}],
\end{aligned}
\tag{24}
$$

where ϑ *denotes the drift and* υ *the volatility of the geometric Brownian consumption for individual consumption,* λ *the probability of a macroeconomic disaster, and* ϕ *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 macroeconomic disaster follows a power distribution, we substitute* $\mathrm{E}[\phi^{1-\gamma}] = \alpha/(\alpha+1-\gamma)$ *and* $\mathrm{E}[\phi^{\beta-\gamma}] = \alpha/(\alpha+\beta-\gamma)$ *into the expressions for* R *and* SCC_0*.*

Proof. The result combines the arguments used to derive equations (20) and (22). □

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 $-\omega\eta h$ in R and the denominator of the expression for the SCC), conventional macro risks (via the term $-(\omega-1)\gamma\upsilon^2/2$), and the risk of rare macroeconomic disasters (via the term $-\lambda\frac{\omega-1}{1-\gamma}\left(1-\mathrm{E}[\phi^{1-\gamma}]\right)$).

Standard macroeconomic uncertainty or risks of rare macroeconomic disasters do not impinge on the discount rate R or the SCC if the aversion to intertemporal fluctuations equals one ($\omega = 1$). If aversion to intertemporal fluctuations exceeds one ($\omega > 1$), higher variance of macroeconomic shocks, a higher risk of rare disasters, and a higher risk aversion decrease R and increase the price of carbon.

The discount rate can be written as $R = r_F + \pi - \beta\vartheta$, where r_F is the safe rate, $\pi = \beta\gamma\nu^2 + \lambda\mathrm{E}[\phi^{-\gamma} - \phi^{\beta-\gamma}] - \frac{1}{2}\beta(\beta-1)\nu^2$ denotes the risk premium and $\beta\vartheta$ corrects for expected growth in marginal damages (see Appendix C). Note that the risk premium is zero if the climate beta is zero. The discount rate R used to calculate the SCC in equation (24) equals the safe rate (r_F) plus the risk premium (π) minus a correction to account for growth in marginal global warming damages ($-\beta\vartheta$).

7 Calibration

Table 1 summarises our benchmark calibration and discuss the sensitivity values for some of the key parameters.

7.1 Global economic activity, growth, and disasters

We assume an average growth of per-capita consumption of approximately 2.0% per year, 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).[11] Moreover, we use the World Development Indicators (WDI) for data on GDP, population, PPP exchange rates and, using 2020 as base year, we set the population to $N = 7.28$ billion and the per-capita level of global GDP (using 2020 $USD at purchasing power parity) to $c_0^{mean} = \$17801$ in 2020.

The conventional macroeconomic risk (captured by geometric Brownian motion) is calibrated with a drift of $\vartheta = 2\%$/year and a volatility of $\upsilon = 2\%/\sqrt{\text{year}}$. Following Barro (2006) and Barro (2009), the macroeconomic disaster risk is calibrated so that the probability of a macroeconomic disaster is $\lambda = 3.5\%$/year corresponding to a mean arrival time for disasters of 29 years and an expected size of a macroeconomic disaster of 8.7% (i.e., $\mathrm{E}[l] = 0.087$), which for the power function distribution yields a parameter of $\alpha = 10.494$.

7.2 World inequality: three scenarios

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 has been almost steadily declining. This latter effect is largely due to convergence due to high economic growth in China and other emerging economies, yet over the last years the decline in inequality has

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

Parameter	Notation	Benchmark Value	Sensitivity
	Preferences		
Intragenerational inequality aversion	η	1	0.5 and 1.5
Relative risk aversion (CRRA)	γ	7.1026	
Benchmark:			
Pure rate of time preference	δ	$1.2195\%/year$	
Intergenerational inequality aversion	ω	1.5	
Alternative:			
Pure rate of time preference	δ	$2.104\%/year$	
Intergenerational inequality aversion	ω	0.6667	
	Economic growth		
Expected Drift	ϑ	$0.02/year$	
Volatility of growth	ν	$0.02/\sqrt{year}$	
Expected disaster loss	$\mathrm{E}[l]$	0.087	
Probability of a disaster	λ	$0.035/year$	
Power function parameter	α	10.494	
Expected loss term	$\mathrm{E}[\phi^{-\gamma}]$	2.919	
Expected loss term	$\mathrm{E}[\phi^{1-\gamma}]$	2.284	
	World Income Distribution		
World consumption per capita (2020)	c_0	\$17801	
Mean of global income distribution (2020)	μ_0	\$8.98	
Coefficient of variation (type 3 inequality)	CV_0	1.41	
Variance of income distribution	$\sigma_0^2 = ln\,(1 + CV_0^2)$	1.100163	
World population	N	7.28 billion	
	Intragenerational Inequality Scenarios		
SSP2: slighly decreasing inequality	h	-0.0063	SSP4: 0.0048 SSP5: -0.0093
	Global Warming Damages and Temperature Response		
Damage parameter	χ_1	3.45% of GDP/$°C$	
Climate Beta	β	1	0, 0.5 and 1.5
Transient climate response (TCRCE)	ξ_1	$1.8°C/GtC$	

Table 1: Calibration: The distributional parameters provide the initial income distribution from which the three SSP inequality scenarios are applied.

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 0.60 in 2020. In particular, for 2020, we estimate a coefficient of variation of $CV_0 = 1.41$. Based on the WDI and SWIID statistics for 2020, 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 21^{st} century.

Our best-guess and benchmark estimate reproduces the inequality level of the av-

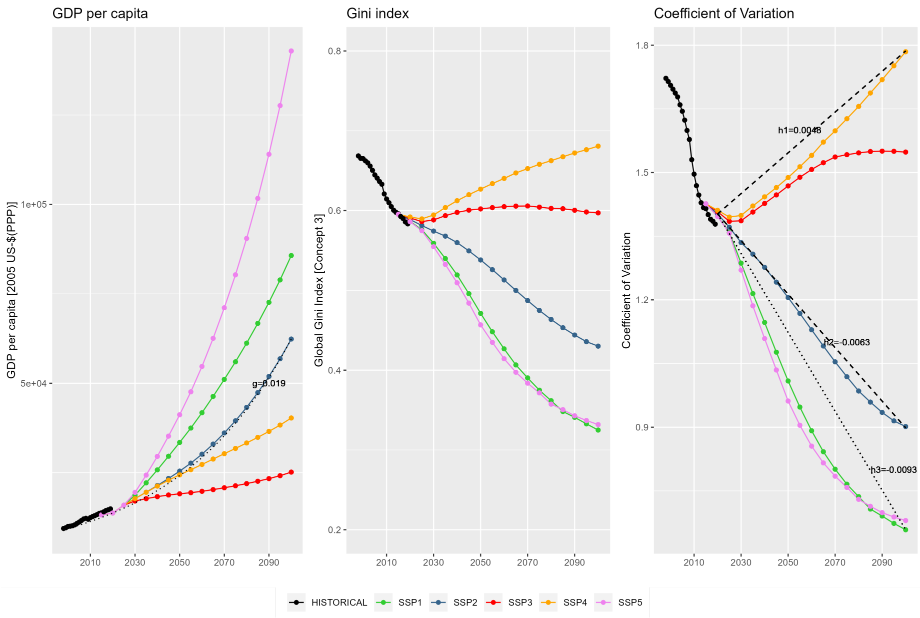

Figure 1: GDP per capita and inequality and for different SSPs Each panel shows historical trends from 1990 until 2020 in, from left to right, per capita GDP, the Gini coefficient, and the coefficient of variation. In each case projections from 2020 to 2100 are based on the SSP scenarios. For the coefficient of variation, the dotted lines reflect the linear trend which we have used to calibrate h in our estimates of the SCC. SSP2 is our benchmark scenario.

erage historical trends scenario SSP2 in 2100 reaching a lower global Gini index of about 0.51. In this benchmark scenario growth is inequality-reducing, leading to our central estimate ($h = -0.0063$) (see the dotted lines in Figure 1).

We consider two further scenarios in our sensitivity exercises. The first scenario SSP4 assumes a slow increase in intragenerational inequality with economic growth, so that h is positive ($h = 0.0048$). The second scenario SSP5 assumes a faster decline in inequality than in our benchmark case ($h = -0.0093$), which reflects the trend in the last decade (indicated by the dashed lines in Figure 1). Figure 1 plots these three SSP scenarios and what our linear characterisation of the associated changes in intragenerational inequality imply for these three scenarios.

Finally, we set the coefficient of intragenerational inequality aversion to $\eta = 1$ with sensitivity of $\eta = 1.5$ and $\eta = 0.5$ reflecting the range seen in the literature (e.g., Groom and Maddison, 2018; Tol, 2010). We consider in section 8.5 also the effects of a wider range for η, since Del Campo et al. (2021) suggest values as high as 3.

7.3 Global warming damages

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 damages being a convex (quadratic) function of temperature. We consider 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 3.45% of GDP per degree Celsius of global warming. This is for the relevant ranges of temperature a much lower figure than implied by the quadratic damage functions used in Nordhaus (2017).[12]

[12]This study calibrates the damage ratio as 0.236% loss in global income per degree Celsius squared. This implies that the marginal damage ratio is 0.944% (i.e., $2 \times 0.236\% \times 2°C$), 1.416% and 2.832% of world GDP at 2, 3 and 6 degrees Celsius relative to the preindustrial level, respectively. Only at 7.3 degrees Celsius the marginal damage ratio corresponds to our choice of $\chi_1 = 0.0345$.

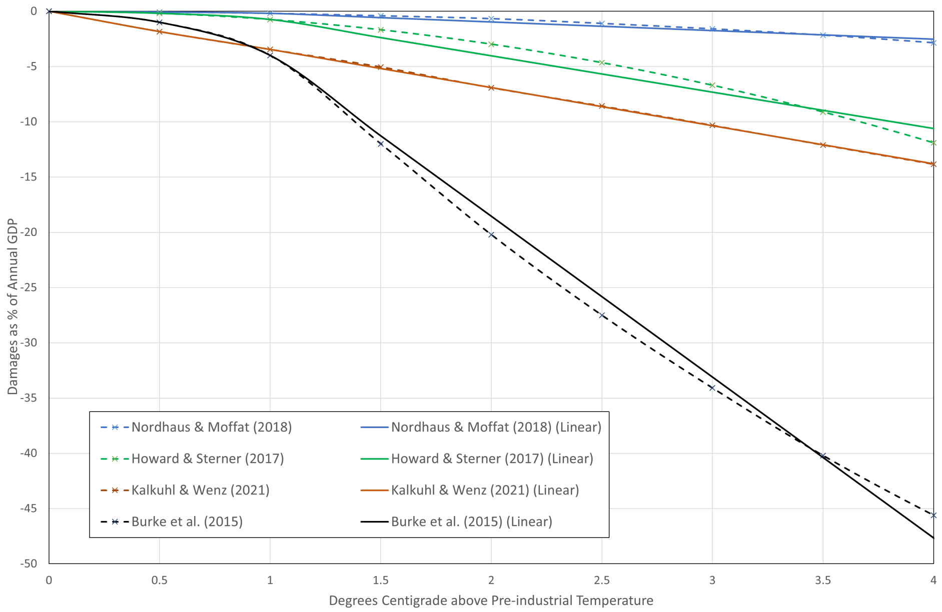

Figure 2: Estimates of Climate Damages as a Proportion of GDP and their Linear Approximations. The figure shows empirical global damage functions from four influential papers on the estimation of climate damages which are routinely referred to in integrated assessment studies: 1) Nordhaus and Moffat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

7.4 Transient climate response to cumulative emissions

For temperature we use a transient climate response to cumulative emissions of 1.8 degrees Celsius per trillion tons of carbon. This value is roughly at the center of the ”likely” range (1.0–2.5°C) of IPCC 5th Assessment Report (AR5).

7.5 Benchmark calibration: EIS < 1

In our benchmark calibration, we follow DICE and assume a coefficient of intergenerational inequality aversion of 1.5 ($\omega = 1.5$), corresponding to to an elasticity of intertemporal substitution of EIS $= 2/3$. Since $\omega > 1$, macroeconomic uncertainty depresses the discount rate R and thus increases the SCC in our benchmark calibration.

We match a macroeconomic risk premium of 2.75%,[13] so that

$$\pi = \gamma\nu^2 + \lambda \mathrm{E}[\phi^{-\gamma} - \phi^{1-\gamma}] = 0.025 \tag{25}$$

[13]Since the equity return is about 8% per year, we match the equity risk premium of 7% per year by assuming that firms are leveraged. Since 7% equals 2.8 times 2.5%, this implies a leverage factor of 2.8. The equity risk premium has no further consequence for our calculations of the SCC.

We know from subsection 7.1 that the volatility of normal macroeconomic shocks is $\upsilon = 2\%/\sqrt{\text{year}}$, the probability of a disaster is $\lambda = 3.5\%/\text{year}$, the expected size of a disaster is 8.7% ($\mathrm{E}[l] = 0.087$), and the power function parameter is $\alpha = 10.494$. Plugging these values in equation (25), using $\phi = 1 - l$, and solving for the coefficient of relative risk aversion gives $\gamma = 7.1026$.

We also match a risk-free interest rate of 1% per year, so that ignoring the effect of growth on intragenerational inequality we have

$$r_F = \delta + \omega\vartheta - \frac{1}{2}(1+\omega)\gamma\nu^2 - \lambda\left[E[\phi^{-\gamma}] - 1 + \frac{\omega-\gamma}{\gamma-1}\left(E[\phi^{1-\gamma}] - 1\right)\right] = 0.01. \quad (26)$$

(cf. equation (A.23) in Appendix C). Given $\omega = 1.5$ and from sub-section 7.1 a drift of normal macroeconomic shocks of ϑ= 2%/year, we use equation (26) to back out the benchmark pure rate of pure time preference of δ =1.2195% per year.

7.6 Alternative calibration: EIS $>$ 1

In macro finance it is often assumed that EIS > 1, i.e., $\omega < 1$, so that macroeconomic uncertainty increases the (growth-adjusted) discount rate and depresses share price. We thus also consider an alternative calibration with EIS > 1 corresponding to $\omega = 2/3$ in which case the EIS $= 1.5$. In that case, macroeconomic uncertainty increases the (growth-adjusted) discount rate and depresses the SCC. Equation (25) still gives the same value of relative risk aversion $\gamma = 7.1026$ but equation (26) now gives the alternative pure rate of time preference of $\delta = 2.104\%$ per year. Both the benchmark and the alternative calibration thus match a safe rate of 1% and a macroeconomic risk premium of 2.75% per year.

8 Quantification of the social cost of carbon

Now we can compute the SCC for our benchmark calibration and for various alternative parameter combinations. Our calibration matches the observed risk-free rate and risk premium in financial markets (see sections 7.5 and 7.6), while our benchmark value for intertemporal inequality aversion ($\omega = 1.5$) is in line with for instance Nordhaus' DICE model. For the degree of intragenerational inequality aversion we use a benchmark value of ($\eta = 1$), which is around the center of the range between 0.5 and 2 or 3 found in the meta study by Del Campo et al. (2021). We explore sensitivity around this benchmark value by also reporting results for η equal to 0.5 and 1.5. Table 2 reports our benchmark results for the SDR and the SCC, and various sensitivity exercises.

8.1 Core result and sensitivity to inequality scenarios

If economic growth is neutral in the sense that it does not affect intragenerational inequality (h =0), the SCC is \$125/tCO_2. If growth is associated with slow convergence in income per capita as in our benchmark (middle-of-the-road) scenario SSP2 with $h = -0.0063$, the SDR increases while the SCC is reduced to \$81/tCO_2. It is further reduced to \$70/tCO_2 when growth is associated with faster convergence in incomes per capita as in the SSP5 scenario. However, if economic growth is associated with increasing inequality per year ($h = 0.0048$) as in the SSP4 scenario, the SDR decreases and the SCC rises to \$213/tCO_2. This latter scenario is not impossible (e.g., Kanbur et al., 2022).

8.2 The climate beta and drivers of the SCC

Table 2 also report the effects of the climate beta on the SDR and the SCC. First, consider the scenario where growth is not associated with changes in intragenerational inequality ($h = 0$). If the climate beta is zero ($\beta = 0$), the SCC equals \$219/tCO_2 compared to \$125/tCO_2 for the case of a unit climate beta. It is much higher since the effects of a zero macro and disaster risk premia dominates the effect of damages no longer growing in line with aggregate consumption, and thus the discount rate used to evaluate the SCC is only 1.7% instead of 1%.

Consider now the benchmark SSP2 scenario where growth is associated with moderate reductions in intragenerational inequality ($h = -0.0063$). The SCC is now \$113/tCO_2 compared to \$219/tCO_2 in the neutral-growth scenario ($h = 0$). So, with a zero climate beta we see that growth that goes together with declining intragenerationaql inequality also leads to lower SCC. Conversely, if growth goes together with increasing inequality as in the SSP4 scenario ($h = 0.0048$), the SCC is much higher, \$784/tCO_2.

Table 2 also reports values for the climate beta of 1.5 and 0.5. Focusing at the benchmark SPP2 scenario, we see that the SCC is now \$82/tCO_2 or \$88/tCO_2, re-

	SSP scenario	Intra. Ineq.	Risk premium	Disaster premium	SDR	R^*	SCC
		%	%	%	%	%	$/tCO$_2$
β	h	(1)	(2)	(3)	(4)	(5)	(6)
1	0	0.0	0.3	2.47	3.7	1.7	125
	0.0048	-0.7	0.3	2.47	3.0	1.0	213
	-0.0063	0.9	0.3	2.47	**4.7**	**2.7**	**81**
	-0.0093	1.4	0.3	2.47	5.1	3.1	70
1.5	0	0.0	0.4	3.32	4.7	1.7	127
	0.0048	-0.7	0.4	3.32	4.0	1.0	217
	-0.0063	0.9	0.4	3.32	5.7	2.7	82
	-0.0093	1.4	0.4	3.32	6.1	3.1	70
0.5	0	0.0	0.1	1.39	2.5	1.5	143
	0.0048	-0.7	0.1	1.39	1.8	0.8	268
	-0.0063	0.9	0.1	1.39	3.5	2.5	88
	-0.0093	1.4	0.1	1.39	3.9	2.9	75
0	0	0.0	0.0	0.00	1.0	1.0	219
	0.0048	-0.7	0.0	0.00	0.3	0.3	784
	-0.0063	0.9	0.0	0.00	1.9	1.9	113
	-0.0093	1.4	0.0	0.00	2.4	2.4	92

Table 2: The relative effects of inequality and uncertainty on the social cost of carbon: benchmark calibration ($\delta = 1.2195\%$, $\eta = 1$, $\omega = 1.5$): The safe interest rate R_f equals 1% per year in all rows. The SDR (4) is the sum of the safe rate,the adjustment for (1) intragenerational inequality aversion ($\omega\eta h$), (2) the risk premium for normal macro uncertainty ($\beta\gamma\nu^2$), (3) the risk premium for disaster risk, and a term which is zero if β is 0 or 1 and a mere -0.02 if $\beta = 1.5$ or 0.01 if $\beta = 0.5$ (i.e., $0.5\beta(\beta-1)\nu^2$). The growth-adjusted SDR (4) equals $R^* = SDR - \beta\vartheta$. The SCC (5) uses this growth-corrected discount rate. The table indicates that if economic growth is associated with falling (rising) intragenerational equality, the SCC will be lower (higher). It also reports the effects of different values of the climate beta β.

spectively, rather than \$81/tCO$_2$ when the climate beta is one. The fact that there is not much difference is that the increases (or decreases) in the macro and disaster risk premia are more or less offset by the increases (decreases) in the correction for growing damages when the climate beta equals 1.5 (or 0.5).

Finally, Table 2 decomposes the value of the SDR into its different components to illustrate their relative effects for different SSP inequality scenarios and for different values of the climate beta. Here the contribution of the safe rate to the SDR is always 1% per year. We see that the disaster premium is the most important driver of the SDR when the climate beta equals one or more, and is then in all cases much bigger than the effects of the macro risk premium associated with geometric Brownian motion shocks. Lower values of the climate beta curbs the effects of the macro and the disaster risk premium on the SDR and thus the SCC smaller. The contribution to the SDR due to intragenerational inequality aversion does not depend on the climate beta, and therefore becomes a more substantial driver of the SDR for low values of the climate beta. In fact, if the climate beta is zero, the correction for intragenerational inequality is the only driver of the SDR (apart from the safe rate which does not vary across the three SSP scenarios).

8.3 Effects of intragenerational inequality aversion

Table 3 shows the effects of different values for the coefficients of relative intergenerational inequality aversion (η). For the benchmark SSP2 scenario, we see that a lower aversion to this type of inequality ($\eta = 0.5$), increases the SCC from \$81/tCO_2 to \$99/tCO_2 while the discount rate reduces from 2.7% to 2.2% per year. A higher intragenerational aversion ($\eta = 1.5$) increases the discount rate to 3.2% per year and curbs the SCC to \$69/tCO_2. The effects are stronger for the SSP5 scenario where economic growth is associated with bigger reduction in intragenerational inequality. However, the effects go the other way around for the SSP4 scenario where economic growth is associated with higher instead of lower intragenerational inequality.

	EDE Approach		Individual Approach	
	R^* (%/year)	SCC (\$/tCO2)	R^* (%/year)	SCC (\$/tCO2)
Benchmark calibration	2.7	81	3.3	66
$\eta = 0.5$	2.2	99	2.5	86
$\eta = 1.5$	3.2	69	4.1	53
Alternative calibration	2.2	101	2.8	78
$\eta = 0.5$	2.0	112	2.3	96
$\eta = 1.5$	2.4	92	3.3	66

Table 3: Comparison of the discount rate and the SCC for benchmark and alternative calibrations and for EDE and individual approaches.: The benchmark and alternative calibration both have coefficient of relative inequality $\eta = 1$ and climate beta $\beta = 1$. All calculations are for the SSP2 scenario. The benchmark calibration has $\omega = 1.5$ and pure rate of time preference $\delta = 1.2195\%$. The alternative has $\omega = 2/3$ and $\delta = 2.104\%$. Each maintains a safe return of 1%. The coefficient of relative risk aversion γ is calibrated to match an annual macro risk premium of 2.75%.

8.4 Alternative calibration with EIS greater than 1

The alternative calibration adjusts the elasticity of intertemporal substitution and the utility discount rate to the same safe rate and macro risk premium, but has an elasticity of intertemporal substitution bigger than one (i.e., 1.5 instead of 0.6667) and a higher utility discount rate (2.104% instead of 1.2195% per year). For the case of neutral growth scenarios that do not affect intragenerational inequality ($h = 0$), the discount rate and the SCC are, of course, not be affected. However, in our benchmark SSP2 scenario economic growth goes together with falling inequality ($h < 0$). Since now the EIS is greater than 1 instead of less than 1, the discount rate for the benchmark is now lower (2.2%) and the SCC is higher (\$101/tCO_2) than with the benchmark calibration. The reason is that the term to correct for intragenerational inequality aversion in the expression for the discount rate, i.e., $-\omega\eta h$, is now smaller given that ω is smaller for the alternative calibration and that $h < 0$ for the SSP2 scenario. Note that the changes go the other way if growth is associated with increasing intragenerational inequality ($h > 0$) as for the SSP4 scenario.

The effects of higher or lower intragenerational inequality aversion are qualitatively the same as for the benchmark calibration.

8.5 Changing intra- and intergenerational inequality aversion

Figure 3 offers a more comprehensive picture of the effects of intra- and intergenerational inequality aversion on the SCC for all the possible alternative calibrations that match a safe rate of 1% and a macro risk premium of 2.5% per year. In practice, this means that for every change in ω from the benchmark value of 1.5, we need to also have a change in the pure rate of time preference δ. To give an idea, as intergenerational inequality aversion ω in Figure 3 varies from 0.5 to 2.5, the pure rate of time preference drops from $\delta = 2.28\%$ to 0.16% per year.[14] The calibration of the safe rate and the macro risk premium in our model is unaffected by changes in the coefficient of intragenerational inequality aversion η.[15] We consider a range for η from 0.5 to 2.5.

Across the three growth and inequality scenarios and these ranges of intra- and intergenerational inequality aversion, Figure 3 indicates a huge range of possibly outcomes for the SCC, varying from the range $\$0/tCO_2 - \$50/tCO_2$ to the range $\$900/tCO_2 - \$1,000/tCO_2$. Let us now examine these results in a little more detail.

Consider the results for our benchmark SSP2 scenario with $h = -0.0063$ (middle

[14] For $\omega > 2.65$, the pure rate of time preference δ is negative.

[15] We suppose that this type of inequality aversion applies not only between countries but also within countries.

panel of Figure 3) first. As intragenerational inequality aversion η increases from 0.5 to 2.5 for any given value of ω, the SCC drops significantly. This is a result of economic growth being associated with falling intragenerational inequality ($h < 0$).

As intergenerational inequality aversion ω increases from 0.5 to 2.5 (and the rate of pure time preference falls to match the observed safe rate), the SCC also drops significantly for any given value of η. There are three effects at play here of a lower ω: (i) typically, the affluence effect and the risk corrections in the discount rate increase which increase the discount rate and lower the SCC; (ii) if $h < 0$, a higher ω increases the discount rate and curbs the SCC but if $h > 0$ the effects are reversed; and (iii) a lower associated value of δ reduces the discount rate and increases the SCC.

It can be shown that the total of these three effects of a marginal change in ω on the discount rate R in Proposition 2 equals $-\eta h$ (see Appendix D). Hence, if $h < 0$ as in the SSP2 and SSP5 scenarios, the discount rate increases and the SCC falls for higher values of ω, But in the SSP4 scenario with $h > 0$, higher values of ω cause falls in the discount rate and increases in the SCC.

The SSP5 scenario with $h = -0.0093$ (right panel of Figure 3) has economic growth associated with stronger falls in intragenerational inequality. As a result, the effects of higher intragenerational inequality aversion η or of higher intergenerational inequality aversion ω is to lead to smaller increases in SCC than in the SSP2 scenario.

Finally, for the SSP4 scenario with $h = 0.0048$ (left panel of Figure 3) economic growth is associated with rising intragenerational inequality. This leads to qualitatively very different results than for the SSP2 and SSP5 scenarios. We now see that higher intragenerational inequality aversion η and higher intergenerational inequality aversion ω leads to big falls in the discount rate and big boosts in the SCC. The top right corner of the left panel is white to indicate that for those combinations of high values of η and ω the discount rate has become negative and the SCC cannot be evaluated.

8.6 Individual versus the EDE approach

The "individual" approach for the marginal evaluation of consumption (see Appendix B) differs in the way marginal changes in consumption are distributed in the economy. This alternative approach has in common with the EDE approach that it takes into account how inequality evolves over time but also allows for the marginal impacts along

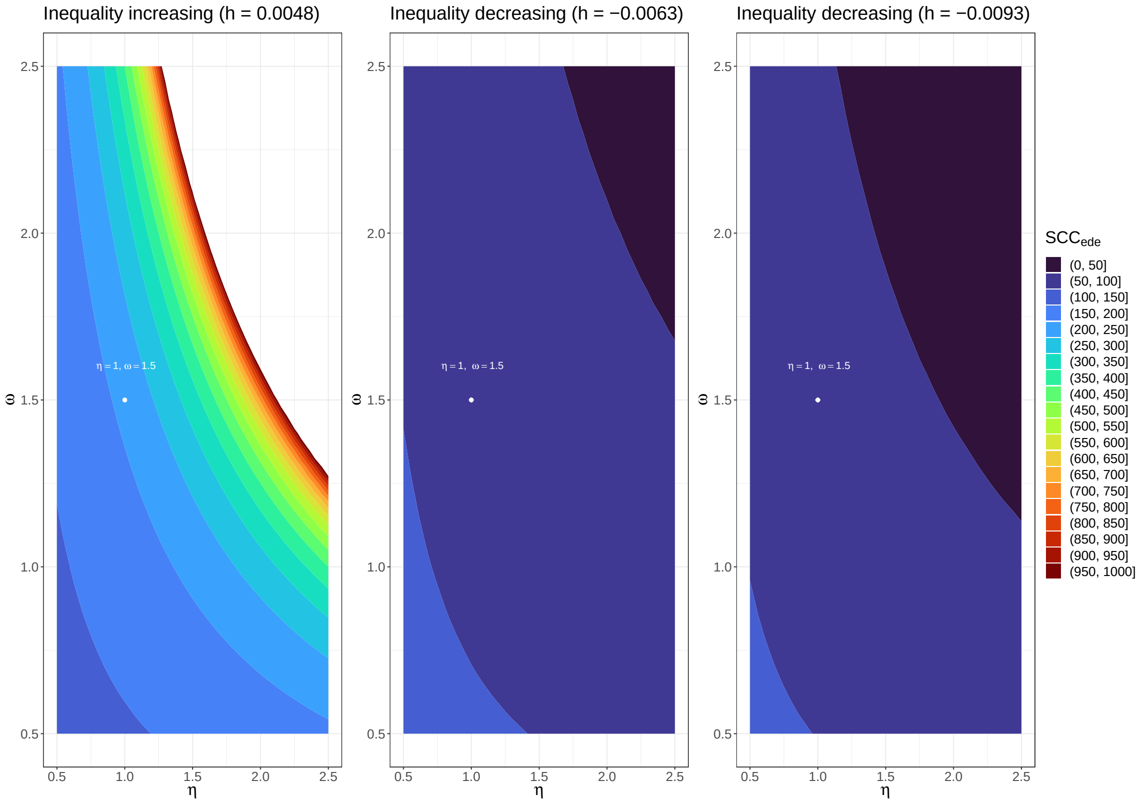

Figure 3: The SCC as function of intragenerational (η) and intergenerational inequality aversion (ω), with stochastic growth of the economy. The SCC is calculated from Proposition 2 in section 6.3. The climate beta is set to one ($\beta = 1$). We depart from the benchmark calibration in that we consider a wide range of values for the coefficient of relative intragenerational inequality aversion η and similarly for the coefficient of intergenerational inequality aversion ω. To ensure, that for all values of ω the observed safe rate of 1% per year is matched, the calibration of the pure rate of time preference δ is adjusted whenever there is a departure of ω from its benchmark value of 1.5. The SSP scenarios are as in Figure 1. Our benchmark scenario SSP2 is shown in the middle panel. The white region in the left panel corresponding to the SSP4 scenario indicates that R is negative and the SCC cannot be evaluated for high values of ω and η.

the distribution at any point in time. The main difference with the EDE approach is that the term to correct for intragenerational inequality aversion in the discount rate of Proposition 2 changes from $-\omega\eta h$ to $-(1+\omega)\eta h$. Since the benchmark SSP2 scenario has economic growth associated with declining inequality ($h < 0$), the discount rate will be larger and thus the SCC will be lower. This is what we see for all rows of Table 3. For example, for the benchmark calibration the SCC falls from \$81/tCO$_2$ to \$66/tCO$_2$ and for the alternative calibration the SCC falls from \$101/tCO$_2$ to \$78/tCO$_2$ when the "individual" approach rather than the EDE approach is used.

In contrast, if economic growth is associated with increasing inequality ($h > 0$) as in the SSP4 scenario, the discount rate will be smaller and the SCC higher. Finally, we note that changing intragenerational inequality aversion does not affect our earlier qualitative insights.

We favour using the EDE above the "individual" approach in part because it is more tractable, but also because assessing and internalising intragenerational inequality for each period using the concept of EDE income seems closer to the way in which policy makers assess social inequality in practice.

9 Discussion: income-dependent damages

Developing countries suffer more from heating of the planet due to extreme droughts, crop failures, etc. Also, within countries it is the poor that suffer more from the collateral damages of global warming (i.e., more fine particles) because they more often live next to roads with heavy traffic. Global warming therefore typically hurts the poor more than the rich. If damages hurt the poor relatively more and policy makers care more about the welfare of the poor than the rich, then the SCC will have to be equity weighted to account for income-dependent damages.[16] It can be shown that the equity-weighted SCC will then be higher than the unweighted SCC of

[16]If 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 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)

Proposition 2 (Mirrlees, 1978; Jacobs and van der Ploeg, 2019).[17] More precisely, if there is a *positive* covariance between impacts of global warming and welfare weights along the income distribution, the equity-weighted SCC exceeds the unweighted SCC.[18]

A complication arises for policy makers. On the one hand, damages hurt the poor more than the rich, and, on the other hand, higher carbon pricing is regressive and hurts the poor also more than the rich. The poor are thus hit twice. This means that it is even more important to redirect the revenue of carbon taxes to the poor.

10 Conclusion

We have shown how to obtain a novel and easy-to-interpret analytical expression for the social discount rate and the social cost of carbon that allows for intra- and intergenerational inequality in society and for intra- and intergenerational inequality aversion. Furthermore, this expression allows for uncertainty in the growth of mean per-capita consumption over time, and the risk of rare macroeconomic disasters. We have used this expression to calculate the SCC based on recently updated estimates of the climate damage function discussed in Kalkuhl and Wenz (2020). We have decomposed and identified the different effects of both dimensions of inequality and uncertainty on the SDR rate and the SCC.

Our key insights are that, if economic growth is associated with decreasing (rising) intragenerational inequality, the SDR rate is higher (lower) and the SCC is lower (higher) 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. Historical data on the global income distribution shows that growth is associated with slowly reducing intragenerational inequality since the 1990s. Considering several scenarios of inequality and economic growth over the 21st century, continuation of this trend seems probable. This trend requires a downward adjustment of the SCC from \$125 to \$81 per ton of emitted CO_2 in our main specification. However, in a less likely and pessimistic scenario where intragenerational

[17] This assumes that the constant χ_0 varies with income. If the temperature sensitivity χ_1 varies with income, the analysis is more complicated.

[18] The equity-weighted Pigouvian tax (or SCC) equals the unweighted sum of marginal damages plus a term that corresponds to the covariance between the relative weight of damages to an individual and the Pareto (or welfare) weight of that individual across all individuals in society (Jacobs and van der Ploeg, 2019).

inequality increases steeply with economic growth, the SCC would have to double to about \$213 per ton of emitted CO_2.

Concerned policymakers find the future less (more) important relative to the present when economic growth is associated with falling (increasing) intragenerational inequality, since then the gap between mean and Equally Distributed Equivalent (EDE) consumption declines (grows) over time. Higher intragenerational inequality aversion makes this effect stronger.

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. In terms of magnitude, the effect of intragenerational inequality on the SDR is to add or take away 1-2% depending on the level of intragenerational inequality aversion (η) and on whether growth is associated with decreasing or increasing intragenerational inequality, with commensurate changes in the SCC. This is smaller than the effect of disaster risk for high values of the climate beta, but bigger for values of the climate beta closer to zero.

We have put forward a framework for evaluating the SDR and the SCC under various types of inequality and risk. We can extend our analysis in the following ways.

First, our analysis can be improved by considering inequality between and within countries. One 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. The ratio of the SCC to aggregate economic activity is then not constant but typically an increasing function of temperature. A perturbation method or a numerical algorithm will need to be used to solve for the simultaneous evolution of temperature, cumulative emissions, the economy, and the SCC.

Third, global warming hurts the poor more than the rich. The calculation of the SCC can take this into account if one can empirically assesses global warming damages for each specific type of individual (see section 9). Furthermore, just as our approach has taken into account catastrophic risks across time, future models ought to assess the more disastrous prospect of catastrophic damages to households or countries with already low incomes, which would increase the welfare effects of climate change.

Fourth, the SDR may decline with the length of the horizon due to persistence in the growth dynamics or uncertainty about the drift or volatility parameters (e.g., Arrow et al., 2013; Gollier, 2007; Weitzman, 2001). See Newell et al. (2022) for a recent policy proposal relating to the SCC.[19]

Finally, a heterogeneous-agent macro model augmented with a climate block in which distributions of incomes and wealth evolve endogenously together with the accumulation of capital is more realistic than an endowment economy.[20] When the tax menu is insufficient and policy makers have to resort to second-best taxes, our expression for the SCC will have to be modified.

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[19] A 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.

[20] The 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).

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Appendix A 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 intragenerational inequality aversion considered. For the lognormal distribution, the growth rate of mean income of any quantile p can be computed as

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

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 $\phi^{-1}(p - quantile) = 1 - \eta$ holds, the given quantile growth rate and EDE growth rate coincide. Hence, $p - quantile = \phi(1 - \eta)$ 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 a unit coefficient of intragenerational inequality aversion (i.e., $\eta = 1$), 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% quantile. This shows how higher coefficients of relative intragenerational inequality aversion leads to a lower quantile corresponding to EDE income. For $\eta = 0$, policy makers do not care about intragenerational inequality which corresponds to the 84% quantile.

Appendix B The individual approach

In the paper we have followed the EDE-based definition of the social welfare function, discount rate, and the SCC. However, in principle intragenerational inequality might affect marginal utilities both today and in the future. For the lognormal case, we apply the bivariate lognormal result of Emmerling (2018) and get

$$r_t^{ind} = \delta + \omega g_t^{mean} + (\omega + 1) g^{1-I_t(\eta)} \tag{A.2}$$

which with non-neutral effects of growth on inequality captured by the value of h gives

$$r_t^{ind} = \delta + \omega g - \eta(1+\omega)h = \delta + \omega(g - \eta h) - \eta h. \tag{A.3}$$

Comparing the EDE approach in (8) with the SDR of the individual approach in (A.3), 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.[21] For the EDE representative agent, this prudence effect is absent.

Now we proceed to compute the SCC at the individual level 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

$$SCC_0(\theta)^{ind} \equiv \frac{N \int_0^\infty e^{-\delta t} \left(\frac{\partial D_t}{\partial T_t}\right) \left(\frac{\partial T_t}{\partial E_t}\right) \left(\frac{\partial E_t}{\partial e_0}\right) \frac{V'(\cdot)}{U'(\cdot)} \int_\theta U'\left(c_t(\theta)\right) dF(\theta) dt}{\frac{V'(\cdot)}{U'(\cdot)} U'\left(c_0(\theta)\right)}. \tag{A.4}$$

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

$$SCC_0(\theta)^{ind} \equiv \frac{N \int_0^\infty e^{-\delta t} \chi_1 {c_t}^{mean} \xi_1 \left(EU_t\right)^{\frac{\eta-\omega}{1-\eta}} \int_\theta c_0(\theta)^{-\eta} dF(\theta) dt}{\left(EU_0\right)^{\frac{\eta-\omega}{1-\eta}} c_0^{-\eta}}. \tag{A.5}$$

Using the moments of the lognormal distribution, we can show that $SCC_0(\theta)^{ind}$ becomes

$$SCC_0(\theta)^{ind} = \frac{1}{c_0^{-\eta} / \int_\theta c_0(\theta)^{-\eta} d\theta} \left(\frac{\chi_1 \xi_1}{\delta + (\omega - 1)g - \eta(1+\omega)h}\right) N c_0^{mean}. \tag{A.6}$$

This value for the SCC is again proportional to aggregate output (see last term), reflects the transient climate response to cumulative emissions, the damage coefficient, and the individual discount rates (second term), and is normalised by the ratio of

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

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 lognormally distributed across individuals as

$$SCC_{0,}(\theta)^{ind} \sim LN(ln(SCC_0^{ind}) + \eta^2 \frac{\sigma_0^2}{2}, \eta^2 \sigma_0^2). \tag{A.7}$$

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 ($\eta \to 0$), 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

$$SCC_0^{ind} \equiv \frac{N \int_0^\infty e^{-\delta t} \left(\frac{\partial D_t}{\partial T_t}\right) \left(\frac{\partial T_t}{\partial E_t}\right) \left(\frac{\partial E_t}{\partial e_0}\right) \frac{V'(\cdot)}{U'(\cdot)} \int_\theta U'\left(c_t(\theta)\right) dF(\theta) dt}{\frac{V'(\cdot)}{U'(\cdot)} \int_\theta U'\left(c_0(\theta)\right) dF(\theta)}. \tag{A.8}$$

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

$$SCC_0^{ind} = \left(\frac{\chi_1 \xi_1}{\delta + (\omega - 1)g - (1 + \omega)\eta h}\right) N {c_0}^{mean}, \tag{A.9}$$

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. If economic growth is associated with rising (falling) intragenerational inequality, i.e., $h > 0$ ($h < 0$), Proposition B.1 implies that the SCC under the *individual* approach is bigger (smaller) than the SCC under the EDE approach provided $\eta > 0$.

The SCC_0^{ind} can also be written as a weighted average of the individual SCC for each individual in the population, i.e.,

$$SCC_0^{ind} = \frac{c_0^{-\eta}}{\int_\theta c_0(\theta)^{-\eta} d\theta} SCC_0^{ind}(\theta). \tag{A.10}$$

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).

Appendix C The SDR and SCC under uncertainty

Social welfare is given by the recursive formulation:

$$W_t \equiv \mathrm{E}_t \left[\int_t^\infty \quad f(c_s, W_s)\, ds \right] \tag{A.11}$$

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,

$$dc^{mean} = \vartheta c^{mean} dt + \nu c^{mean} dW - l c^{mean} dZ, \tag{A.12}$$

where Z 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, $\phi \equiv 1 - l$, have a power distribution $h(\phi) = \alpha\phi^{\alpha-1}$ with $\alpha > 0$ defined on the interval $\phi \in (0, 1)$, so that $\mathrm{E}[\phi^n] = \frac{\alpha}{\alpha+n}$.

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., $\chi_1\zeta_1 Nc$, 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. *Abstracting from intragenerational inequality, the SCC is*

$$SCC_t = \frac{\chi_1\zeta_1}{R} N c_t^{mean}, \tag{A.13}$$

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

$$R = \delta + (\omega - 1)\left(\vartheta - \frac{1}{2}\gamma v^2 - \frac{\lambda}{1-\gamma}\left(1 - \mathrm{E}[\phi^{1-\gamma}]\right)\right). \tag{A.14}$$

Proof. We abstract from intragenerational inequality and inequality aversion, so that c_t refers to consumption of the representative consumer or mean consumption at time t. For ease of notation, we thus omit the superscript "mean" in this proof. The value function $W = W(C)$ gives welfare to go for the problem of maximising (A.11) subject to (A.12) and solves the Hamilton-Jacobi-Bellman equation

$$0 = f\left(c, W\left(c\right)\right) + W'\left(c\right) c\vartheta + \frac{1}{2}W''\left(c\right) c^2 v^2 + \lambda \mathrm{E}\left[W(\phi c) - W(c)\right] \tag{A.15}$$

Conjecture that the value function has the form $W\left(c\right) = \frac{(Xc)^{1-\gamma}}{1-\gamma}$, so $W'(c) = X^{1-\gamma}\ c^{-\gamma}$ and $W''(c) = -\gamma X^{1-\gamma}\ c^{-\gamma-1}$. Upon substitution into equation (A.15) and dividing by $(Xc)^{1-\gamma}$, we obtain

$$0 = \frac{\delta}{1-\omega}\left(X^{\omega-1} - 1\right) + \vartheta - \frac{1}{2}\gamma\nu^2 + \frac{\lambda}{1-\gamma}\left(\mathrm{E}\left[\phi^{1-\gamma}\right] - 1\right). \tag{A.16}$$

This can be solved for the constant

$$X = \left[1 - \frac{1-\omega}{\delta}\left\{\vartheta - \frac{1}{2}\gamma\nu^2 + \frac{\lambda}{1-\gamma}\left(E\left[\phi^{1-\gamma}\right] - 1\right)\right\}\right]^{\frac{1}{\omega-1}}. \tag{A.17}$$

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

$$H_t = \exp\left(\int_0^t f_W\left(c_s, W_s\right) ds\right) f_c\left(c_t, W_t\right), \tag{A.18}$$

where equation (A.18) implies that the SDF satisfies

$$\frac{dH}{H_-} = \frac{df_c(c_-, W_-)}{f_c(c_-, W_-)} + f_W(c, W)dt. \tag{A.19}$$

From equation (A.11), $f_C = \frac{\delta c^{-\omega}}{[(1-\gamma)W]^{\frac{1}{\theta}-1}} = \delta c^{-\gamma} X^{\omega-\gamma} \equiv g(c)$. Ito's lemma gives $df_c(c_-, W_-) = dg(c) = g'(c)dc^c + \frac{1}{2}g''(c)c^2\nu^2 dt + (g((1-l)c) - g(c))\,dJ$, where c^c indicates the continuous part of the process for c (ignoring jumps), so that $\frac{dg(c)}{g(c_-)} = -\gamma(\vartheta dt + \nu dZ) + \frac{1}{2}\gamma(1+\gamma)\nu^2 dt + [\phi^{-\gamma} - 1]\,dJ$. Using these two relationships, equation (A.19) gives

$$\frac{dH}{H_-} = f_W dt - \gamma(\vartheta dt + \nu dZ) + \frac{1}{2}\gamma(\gamma+1)\nu^2 dt + \left[\phi^{-\gamma} - 1\right] dJ. \tag{A.20}$$

Using $\theta - 1 = \frac{\omega-\gamma}{1-\omega}$ and the value function with X from equation (A.17), we obtain

$$\begin{aligned} f_W = &\\ &\delta(\theta-1)\,c^{1-\omega}[(1-\gamma)W]^{-\frac{1}{\theta}} - \delta\theta = \delta(\theta-1)X^{\omega-1} - \delta\theta \\ &= -\delta - (\omega-\gamma)\left\{\vartheta - \frac{1}{2}\gamma\nu^2 + \frac{\lambda}{1-\gamma}\left(E\left[\phi^{1-\gamma}\right] - 1\right)\right\}. \end{aligned} \tag{A.21}$$

In equilibrium, the risk-free discount rate equals *minus* the expected rate of change of the SDF, so that (using equations (A.19) and (A.20) and $E[dZ] = 0$) we have

$$r_F = \delta + \omega\vartheta + (\omega-\gamma)\left[-\frac{1}{2}\gamma\nu^2 + \frac{\lambda}{1-\gamma}\left(E\left[\phi^{1-\gamma}\right] - 1\right)\right] - \frac{1}{2}\gamma(\gamma+1)\nu^2 - \lambda E\left[\phi^{-\gamma} - 1\right]. \tag{A.22}$$

Collecting terms, we obtain

$$r_F = \delta + \omega\vartheta - \frac{1}{2}(1+\omega)\gamma\nu^2 - \lambda\left[E[\phi^{-\gamma}] - 1 + \frac{\omega-\gamma}{\gamma-1}\left(E[\phi^{1-\gamma}] - 1\right)\right]. \tag{A.23}$$

Note that the term structure for the safe rate is flat. The SCC is the expected present discounted value of all marginal damages from emitting one ton of carbon today and is thus obtained from

$$SCC_t = \mathrm{E}\left[\int_t^\infty H_{s-t}\chi_1\zeta_1 N c_{s-t} ds\right] = \chi_1\zeta_1 N \mathrm{E}\left[\int_t^\infty G_{s-t} ds\right], \tag{A.24}$$

where $G \equiv Hc$. Combining equations (A.20) and (A.12) and using Ito's lemma, we obtain

$$
\begin{aligned}
\frac{dG}{G_-} = \frac{dH}{H_-} + \frac{dc}{c_-} + \frac{d\langle H, c\rangle}{H_- c_-} &= f_W dt + (1-\gamma)(\vartheta dt + \nu dZ) \\
&\quad + \frac{1}{2}\gamma(\gamma+1)\nu^2 dt - (1-\phi)dJ + (\phi^{-\gamma}-1)dJ + \frac{d\langle H, c\rangle}{H_- c_-},
\end{aligned} \tag{A.25}
$$

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 $(dZ_t)^2 \sim N(0, dt)$ and ignoring terms such as $dtdZ$ and $(dt)^2$, $d\langle c\rangle_t \equiv (dc_t)^2 = \nu^2 dt$, $d\langle H\rangle_t = \gamma^2\nu^2 H dt$, and $d\langle H+c\rangle_t = (c-\gamma H)^2\nu^2 dt$. Note that these terms do not involve the non-continuous parts. Also, $\frac{\mathrm{E}[d\langle H,c\rangle]}{H_- c_-} = -\gamma\nu^2 dt + \lambda \mathrm{E}[(1-\phi)(1-\phi^{-\gamma})]dt$, where the first and second term capture the correlation between the stochastic discount factor H and the process for consumption due to the geometric Brownian motion and the common jump term, dJ, respectively. Substituting this and expression (A.21) into equation (A.25) 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.,

$$
R = \delta + (\omega - 1)\left(\vartheta - \frac{1}{2}\gamma\upsilon^2 - \frac{\lambda}{1-\gamma}\left(1 - \mathrm{E}[\phi^{1-\gamma}]\right)\right). \tag{A.26}
$$

The sum of the prudence term, $-\frac{1}{2}(1+\omega)\gamma\nu^2$, and the risk premium for normal macroeconomic uncertainty, $\gamma\nu^2$, gives the term $-(\omega-1)\frac{1}{2}\gamma\nu^2$ in equation (A.26). The term $-(\omega-1)\frac{\lambda}{1-\gamma}(1-\mathrm{E}[\phi^{1-\gamma}])$ allows for the risk of macroeconomic disasters. Equation (A.26) corresponds to equation (A.14) of Proposition C.1 Equations (A.23) and (A.26) indicate that the discount rate used to calculate the SCC, R, equals the safe rate, r_F, plus the risk premium, $\pi = \gamma\nu^2 + \lambda\mathrm{E}[\phi^{-\gamma} - \phi^{1-\gamma}]$ minus expected growth if the economy and marginal damages, so that $R = r_F + \pi - \vartheta$. The SCC is obtained by substituting (A.19) into (A.17).

□

The safe rate (A.23) corresponds to Hambel (2021, equation (6.3)) (without temperature interaction risk). Various special cases of the discount rate (A.26) 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 0^{th}-order growth rate to ϑ) in line with equation (A.26).

To allow for intragenerational inequality, note that the drift of EDE consumption is $\vartheta - \eta h$, 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 $dc^{EDE} = (\vartheta - \eta h)cdt + \nu cdW - lcdJ$. We thus have $R = \delta + (\omega - 1)\left(\vartheta - \frac{1}{2}\gamma\upsilon^2 - \frac{\lambda}{1-\gamma}\left(1 - \mathrm{E}[\phi^{1-\gamma}]\right)\right) - \omega\eta h$ or $R = \delta + (\omega - 1)\left(\vartheta - \frac{1}{2}\gamma\nu^2 - \frac{\lambda}{1-\gamma}\frac{1-\gamma}{\alpha+1-\gamma}\right) - \omega\eta h$. The term to correct for growing damages depends on mean consumption and not on EDE consumption and thus does not affect the growing damages term in the discount rate: ηh is multiplied by ω not $\omega - 1$. Note also that in the proof above H is now a function of c^{EDE} rather than of $c = c_{mean}$, and similarly G is now defined as $H(c^{EDE})c_{mean}$. We thus have the SCC given in Proposition 2,

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

$$SCC_t = E\left[\int_t^{\infty} \chi_1\zeta_1 H_{s-t} N c^{\beta}_{s-t}\right] = \chi_1\zeta_1 N E\left[\int_t^{\infty} G_{s-t} ds\right], \tag{A.27}$$

where $G \equiv HC = Hc^{\beta}_{mean}$. Using the same procedure as before, we obtain the discount rate, R given by equation (24) and the SCC given by equation (23).

Appendix D Effects of intergenerational inequality aversion and R

The partial derivative of R with respect to ω for the case of $\beta = 1$ is

$$\partial R/\partial\omega = \left(\vartheta - 0.5\gamma\upsilon^2 - \frac{\lambda}{1-\gamma}\left[1 - \mathrm{E}\left[\phi^{1-\gamma}\right]\right]\right) - \eta h. \tag{A.28}$$

To keep the safe rate affected when we change ω, δ must fall by

$$\partial r_F/\partial\omega = \left(\vartheta - 0.5\gamma\upsilon^2 - \frac{\lambda}{1-\gamma}\left[1 - \mathrm{E}\left[\phi^{1-\gamma}\right]\right]\right). \tag{A.29}$$

Hence, we have

$$dR/d\omega = \partial R/\partial\omega + (\partial R/\partial\delta)(\partial\delta/\partial\omega) = \partial R/\partial\omega - \partial r_F/\omega = -\eta h. \tag{A.30}$$

The total marginal effect of a change in ω thus equals $-\eta h$. An increase in ω increases the discount rate if $h < 0$ but reduces the discount rate if $h > 0$.