Journal of Environmental Economics and Management 107 (2021) 102450

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

The social cost of carbon and inequality: When local redistribution shapes global carbon prices

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ARTICLE INFO

Article history:
Received 20 December 2019
Revised 16 March 2021
Accepted 29 March 2021
Available online 5 April 2021

JEL classification:
C61
H21
H23
H41
H77
Q54

Keywords:
Optimal taxation
Inequality
Climate change
Social cost of carbon
Carbon tax

ABSTRACT

The social cost of carbon is a central metric for optimal carbon prices. Previous literature shows that inequality significantly influences the social cost of carbon, but mostly omits heterogeneity below the national level. We present an optimal taxation model of the social cost of carbon that accounts for inequality between and within countries. We find that climate and distributional policy can generally not be separated. If only one country does not compensate low-income households for disproportionate damages, the social cost of carbon tends to increase globally. Optimal carbon prices remain roughly unchanged if national redistribution leaves inequality between households unaffected by climate change and if the utility of households is approximately logarithmic in consumption.

1. Introduction

The social cost of carbon (SCC) is a central measure for climate policy that is used as a guideline for carbon pricing in regulatory impact assessments.[1] The SCC measures the additional damage caused by an extra unit of emissions. Most estimates however omit that the SCC is critically influenced by normative assumptions about distributional justice below the national level – for example if damages to low-income groups are not compensated. We explicitly account for this type of heterogeneity by abandoning the assumption of the traditionally-used national representative agent. Our approach yields corrected estimates

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[1] See Watkiss and Hope (2011); Greenstone et al. (2013); US Interagency Group (2016); Environment and Climate Change Canada (2016); Vinson and Elkins (2016).

https://doi.org/10.1016/j.jeem.2021.102450
0095-0696/

of the SCC as well as new insights into how local redistribution is linked with the level of the SCC on a global scale. We extend the existing literature in two respects.

First, methodologically: We propose a novel model that accounts for heterogeneity both between and within countries by integrating two levels of governance. At the global level, the SCC is a normative benchmark for efficient climate policy. At the national level, distributional policy determines inequality between households. To capture how national redistribution and global climate policy interact, we use an optimal taxation approach: the SCC is the optimal carbon tax regime of a global social welfare function.[2] The derived SCC is country-specific and defines how much each country should reduce emissions from the global perspective.

Second, as a consequence of our methodological choices, the SCC depends on how governments within each country adjust their redistributional policy in response to climate damages and climate policy. We specifically consider national redistribution that is optimal - that is, in accordance with national preferences for inequality. In this case, the SCC is roughly equivalent to the case of a national representative agent if the utility of households is approximately logarithmic in consumption.[3] In contrast, if national redistribution is suboptimal and low-income households in one country are not compensated for disproportionate climate damages, the SCC tends to increase in all countries. In this case, studies that assume no household heterogeneity at the subnational level underestimate the SCC.

For policy making, this indicates that ignoring heterogeneity within countries when determining climate policy can increase inequality between households, and thereby also affect inequality between countries. A policy maker with the objective to mitigate global climate change and inequality simultaneously – as in the context of the Sustainable Development Goals (UN, 2018) – needs to account for interactions between these policies.

Our article builds on two strands of literature. The first strand comprises articles on the derivation and determinants of the level of the SCC (Stern, 2008; Foley et al., 2013; van der Ploeg and Withagen, 2014; Engström and Gars, 2015). The majority of this literature derives estimates of the SCC from Integrated Assessment Models (Greenstone et al., 2013; Metcalf and Stock, 2017) and their analytical counterparts (van den Bijgaart et al., 2016; Golosov et al., 2014; Rezai and Van der Ploeg, 2016; Anthoff and Emmerling, 2019). These models often aggregate the global economy to one representative agent (Nordhaus, 2014, 2017; van der Ploeg and Rezai, 2019) or use Negishi weights in regionalized studies, which render the existing level of inequality optimal within the global social welfare function (Nordhaus and Yang, 1996). Within this literature, we draw on studies that focus on regional inequality and assume welfare weights that deviate from Negishi weights. A social welfare function with general welfare weights allows for different normative assumptions about distributional justice. Chichilnisky and Heal (1994) show that country-specific SCC are optimal for heterogeneous countries when welfare weights differ from Negishi weights and there are no lump-sum transfers between countries. Azar and Sterner (1996), Anthoff et al. (2009), Anthoff and Tol (2010) [4] and Adler et al. (2017) estimate the SCC when countries and regions differ in their consumption and for different assumptions about social preferences for equity. They show that national and regional inequality critically influences the level of the SCC. We extend this literature by including household heterogeneity and endogenous redistribution at the subnational level.

To avoid a bias in the estimates of the SCC, models need to include heterogeneity within countries (Burke et al., 2016). All studies above, however, assume a representative agent at the global, regional or national level. As exceptions, Dennig et al. (2015), Budolfson et al. (2017) and Budolfson and Dennig (2020) estimate optimal carbon taxes under different assumptions about subregional inequality. In addition, Anthoff et al. (2009) and Anthoff and Emmerling (2019) present analytical expressions for the SCC that account for within-country inequality. Our study also accounts for subregional heterogeneity, but, contrary to all previous studies, we take into account that household inequality is not a given characteristic. Instead, allocation between households is determined by distributional policies of national governments (Wang et al., 2012) and thus damages to households may be compensated. We show that estimates of the SCC with national redistribution may considerably differ from studies with exogenous distributions and from models that abstract from inequality. To that end, we compare the SCC under subnational inequality to the case of equality within countries, i.e. the case of national representative agents.

The second strand determines policies under incomplete information (Mirrlees, 1971; Kolev and Prusa, 2002; Jacobs and de Mooij, 2015; Jacobs and van der Ploeg, 2019). This literature assumes information asymmetries between national governments and individuals or firms. Policies are designed respecting private information. Our framework differs from these models in one key aspect: the information asymmetry arises between the global and national levels of governance, not between national governments and households. At the global level, the distributions of income, costs and damages are known but not the identity of households – this prevents redistribution at the global level. Only the national government can redistribute. To our knowledge this approach is novel to the literature on the social cost of carbon (it is related, however, to considerations of environmental and fiscal federalism, see Williams 2012; Roolfs et al., 2020).

[2] Throughout the manuscript we use the terms *social cost of carbon* and *optimal carbon tax* interchangeably. We are aware that, if national redistribution is not optimal from the global perspective, carbon taxes are second-best and might not be considered to equal the SCC by some scholars. We therefore provide a definition of the SCC employed here in Sec. 2.2.

[3] This case is relevant as the literature on the SCC often assumes an isoelastic utility function with the elasticity of marginal felicity equal to unity (Manne and Richels, 2005; Stern, 2006; Golosov et al., 2014). Many other studies choose elasticities that diverge from unity but are still below 2 (Nordhaus, 2017; Barrage, 2018).

[4] Anthoff and Tol (2010) analyze different welfare functions of the national social planner in a setting with regional inequality but no heterogeneity at the subnational level. In contrast to our model, however, they analyze different assumptions regarding the extent to which other countries' welfare is accounted for in each country's welfare, while we analyze different assumptions about redistribution between individual households within countries.

In our model, the SCC is determined at the global level through the maximization of a social welfare function while the national level allocates consumption between households and compensates them for climate change damages and abatement costs. As in Chichilnisky and Heal (1994), we explicitly exclude transfers between countries to focus on the more plausible case of different SCC across countries, and hence country-specific carbon taxes (see also Bataille et al., 2018). Country-specific carbon taxes are consistent with a globally optimal tax regime in the following sense. Traditional optimal taxation theory models only the national level. At this level, income taxation is available to alleviate equity concerns between heterogeneous households. Therefore, optimal carbon taxes can be anonymous, i.e. the tax does not depend on the income or consumption of households (Gauthier and Laroque, 2009; Jacobs and de Mooij, 2015; Fleurbaey and Kornek, 2021). Our study, however, takes a global perspective and hence there is no income taxation to alleviate equity concerns between countries. As a consequence, country-specific carbon taxes can be optimal because they internalize the climate externality subject to different distributional constraints (see Chichilnisky and Heal 1994; Sheeran 2006).

We completely characterize the SCC in this two-level governance setting. The global social welfare function exhibits welfare weights, which we do not further specify. The weights may demand anything, from equality to maintaining current levels of inequality, or reaching any other inequality level between households.

The main analysis focuses on two redistribution schemes. First, national governments choose transfers to maximize a national social welfare function, thus allocating abatement costs between households and compensating for climate damages. Transfers are nationally optimal and mimic the tax and welfare system of each country. We find that the SCC remains roughly unchanged compared to the case of equality within countries if household utility is of the isoelastic form and the elasticity of marginal felicity is close to unity. Under the – in previous literature common – assumption that utility is logarithmic, the SCC is equal to the case of equality within countries. The SCC remains roughly unchanged irrespective of whether global preferences over inequality align with the national level or not. Optimal climate policy can approximately be separated from national distributional policy. This is a consequence of the national level compensating the households in its country for excessive damages.

In the second scheme, the national level reimburses households exactly what they paid in taxes. National distribution is suboptimal as the distribution of climate damages and abatement costs is not taken into account. This models settings, in which governments fail to compensate parts of the population, for example due to capacity constraints. We show that when low-income households experience large and uncompensated climate damages while abatement costs are proportional to income, the SCC tends to increase globally. That is unless preferences for equity at the global level align with inequality. Because national governments fail to compensate low-income households, climate policy ambition increases to avoid impacts on low-income households.

We relax the assumption of no international transfers in an extension to our model and demonstrate that our general insights for the case of no international transfers remain valid. When international transfers are unlimited and are used for nationally optimal redistribution or for redistribution in proportion to household income within countries, the SCC is equal in all countries and its level is still influenced by subnational inequality. This also applies when international transfers are available but restricted.

In a second extension, we quantify the influence of household inequality and national redistribution on the SCC by using a variant of the NICE model (Dennig et al., 2015). We show that the SCC is four times larger for some regions compared to equality when national redistribution is suboptimal and the households in each region experience the same absolute and uncompensated climate damage. In contrast, the SCC changes moderately when redistribution is nationally optimal with a maximum increase of roughly 40% for the parameter range considered.

The article is structured as follows. We describe the model in Sec. 2. In Sec. 3 we derive the main results analytically. Sec. 4 introduces international transfers and uses numerical methods to extend the analytical results. Sec. 5 concludes.

2. A social cost of carbon model with inequality between households

This section first describes our optimal taxation model and introduces the choice of households, the choice of the national governance level and the objective at the global governance level. We then present the concept of the SCC employed to account for inequality within countries, thus adding an additional layer of heterogeneity to models that only account for regional inequality (Azar and Sterner, 1996; Anthoff and Tol, 2010; Adler et al., 2017).

2.1. The model

Our model is based on Chichilnisky and Heal (1994), who study the optimal carbon tax under inequality between N countries. We extend the model by making it dynamic and by accounting for inequality between households. In the following, we use lower case letters to denote variables/parameters at the household level. A bar indicates the mean of the variable/parameter over household distributions within a country. Upper case letters are aggregate variables/parameters at the country level. For a complete list of symbols see Appendix A.10.

Households: In each country $k \in \{1, \ldots, N\}$, there are $H_{t,k}$ households at time $t \in \{0, \ldots, t_{\text{end}}\}$. Households are represented by their respective income n-tile with the same number of persons per household in every country. Each household $j \in \{1, \ldots, H_{t,k}\}$ derives its utility (u) from consumption ($\mathrm{c}_{t,k,j}$) and from the aggregate abatement of a global stock pollutant with zero decay rate. The stock of abatement A_t is hence a global public good and given by the sum of the individual abatement of all households $a_{t,k,j}$ from all previous time steps:

$$A_t = \sum_{T=0}^{t} \sum_{k=1}^{N} \sum_{j=1}^{H_{T,k}} a_{T,k,j}.$$

We distinguish, without loss of generality, two kinds of benefits from abatement. First, households experience monetary damages from climate change. Monetary benefits of abatement are equal to avoided damages and are additive to the consumption of households. Composite consumption is $c_{t,k,j} - d_{t,k,j}(A_t)$. The functional form of damages is given with $\frac{\partial d_{t,k,j}}{\partial A_t} < 0$ and $\frac{\partial^2 d_{t,k,j}}{\partial {A_t}^2} \geq 0$. Monetary damages have been estimated in the literature (Tol, 2002; Hope, 2006) and represent impacts in sectors such as agriculture, energy services and forests. In models that include a production function (Nordhaus, 2017; Barrage, 2020), monetary damages usually affect consumption indirectly by reducing production. As our model does not feature a production function and to focus on the effect of household inequality and optimal carbon prices, we model monetary damages as an additive part of composite consumption.

Second, there are non-market benefits, accounted for in the second argument of the utility function $u(c_{t,k,j} - d_{t,k,j}(A_t), g_{t,k}(A_t))$. The function $g_{t,k}$ converts aggregate abatement of emissions to the quality of each country's climate. Non-market benefits make up a large part of the impact of climate change and increase the level of the SCC (Sterner and Persson, 2008; Drupp and Hänsel, 2020). Constant elasticity utility functions have been used to specify the relative importance of consumption and quality of the environment, usually assuming a global representative agent (Sterner and Persson, 2008; Weitzman, 2010; Drupp and Hänsel, 2020). We adopt previous approaches in the literature and assume homogeneous preferences across households, but where the marginal willingness to pay depends on income (Andreoni and Levinson, 2001; Ebert, 2003; Baumgärtner et al., 2017). Incorporating both monetary and non-market benefits allows us to explicitly study how changes in consumption through monetary damages and redistribution interact with the marginal willingness to pay for the environment, and how both affect the SCC.

We make the standard assumption that composite consumption is positive $c_{t,k,j} - d_{t,k,j} > 0$ and that marginal utility of consumption is continuous, positive and decreasing over this domain: $\frac{\partial u(c_{t,k,j} - d_{t,k,j}, g_{t,k}(A_t))}{\partial c_{t,k,j}} = muc_{t,k,j} > 0$, $\frac{\partial muc_{t,k,j}}{\partial c_{t,k,j}} = mucc_{t,k,j} < 0$. The same holds for the marginal utility of abatement in non-market benefits, $\frac{\partial u(c_{t,k,j} - d_{t,k,j}, g_{t,k}(A_t))}{\partial A_t} = mua_{t,k,j} > 0$, $\frac{\partial mua_{t,k,j}}{\partial A_t} \leq 0$, where the derivative is only with respect to the second argument of the utility function.

Households are heterogeneous in their consumption $c_{t,k,j}$, income $i_{t,k,j}$, abatement costs $m_{t,k,j}(a_{t,k,j})$ and business-as-usual emissions $e_{t,k,j}$ less abatement $a_{t,k,j}$.[5] Abatement costs are strictly convex. Households pay the carbon tax $\tau_{t,k}$ for their residual emissions. In addition, they receive an individualized transfer $\ell_{t,k,j}$, which adds to their disposable income. Note that generally the transfer can be negative. The budget constraint of households is given by:

$$c_{t,k,j} + \tau_{t,k}(e_{t,k,j} - a_{t,k,j}) + m_{t,k,j}(a_{t,k,j}) = i_{t,k,j} + \ell_{t,k,j}. \tag{1}$$

Note that climate change damages are exogenous to households. This is a standard assumption in models of optimal environmental taxation (see Ballard et al., 2005; Barrage, 2020; Jacobs and de Mooij, 2015; Klenert et al., 2018). The model has the following variables: household abatement $a_{t,k,j}$ (determined by households), the transfer $\ell_{t,k,j}$ each household receives from pollution tax revenue and further redistribution between households (determined at the national level), and the carbon tax rate of each country $\tau_{t,k}$ (determined at the global level).

The carbon tax and transfers are exogenous to households. Optimizing their utility subject to the budget constraint, they perform abatement cost-efficiently:

$$\frac{\partial m_{t,k,j}(a_{t,k,j})}{\partial a_{t,k,j}} = \tau_{t,k}, \quad \forall j. \tag{2}$$

Tax rates determine abatement of households. Below, we thus represent abatement by a function $a_{t,k,j}(\tau_{t,k})$, implicitly defined by (2).

National governance level: The national governance level chooses the individualized lump-sum transfer $\ell_{t,k,j}$ that each household in its country receives. More than the total amount of revenue from the carbon tax may be redistributed between households. To close the national budget, the sum of transfers has to equal the tax revenue $\sum_j \ell_{t,k,j} = \tau_{t,k} \cdot \sum_j (e_{t,k,j} - a_{t,k,j}), \forall k, t$.

In the real world, governments face several constraints when redistributing between households. For instance, they cannot know the actual skill level of households and thus have to redistribute using income taxes and respecting incentive constraints, so as to not incentivize households to pretend having different skill levels (Mirrlees, 1971). The purpose of the redistribution through lump-sum transfers is simply to mimic a tax and transfer system at the national level. We chose this reduced-form representation to keep the analysis tractable as much as possible while still representing subnational inequality and redistribution.

The national level redistributes based on its preferences for equity and possibly facing capacity constraints. We represent the choice through generic constraints: the transfer $\ell_{t,k,j}$ is defined by the implicit equation $f_{t,k,j}(\ell_{t,k,1}, \ldots, \ell_{t,k,H_{t,k}}, A_t, \tau_{t,k}) = 0$, and

[5] We omit the channel described in (Sager, 2019) where household emissions additionally depend on the after-tax income of households, which would lead to a feedback between redistribution and total emissions, as redistribution could lead to an increase in emission which in turn would influence the SCC ("equity-pollution dilemma").

we assume that a solution exits. The functions f capture national preferences and constraints. They depend on the endogenous variables of the model: the level of transfer to all households in that country, the stock of abatement and the tax rate of the country. You may think that each constraint explicitly defines the transfer to that household based on the variables of our problem (even though transfers can only be implicitly defined for the case of nationally optimal transfers below).

Appendix A.1 solves the model for generic constraints. Sec. 3 analyzes nationally optimal and nationally suboptimal transfers.

Global governance level: Optimal climate policy is determined at the global level through the maximization of a global social welfare function (SWF). Optimal policies are constrained Pareto-efficient. The social welfare function aggregates each household's utility with global welfare weights $w_{t,k,j}$ so that efficiency in the Pareto sense holds (Chichilnisky and Heal, 1994) but the optimization is subject to constraints on redistribution. First, as in Chichilnisky and Heal (1994), we exclude transfers between countries to focus on the case where optimal carbon taxes differ between countries. Chichilnisky and Heal (1994) show that when allowing for unrestricted international transfers, optimal carbon taxes are equal among countries. We are particularly interested in the consequences of relaxing this assumption, but analyze the consequences of international transfers in Sec. 4.1 below. Second, national transfers between households in each country are determined by national institutions.

The objective at the global level is given by:

$$\max_{\tau_{t,k},\ell_{t,k,j}} \text{SWF} = \sum_{t=0}^{t_{\text{end}}} \frac{1}{(1+\rho)^t} \sum_{k=1}^{N} \sum_{j=1}^{H_{t,k}} w_{t,k,j} \cdot \text{u}(\text{c}_{t,k,j} - \text{d}_{t,k,j}, \text{g}_{t,k}(\text{A}_t))$$

$$\text{s.t.} \quad \text{f}_{t,k,j}(\ell_{t,k,1}, \ldots, \ell_{t,k,H_{t,k}}, \text{A}_t, \tau_{t,k}) = 0, \quad \forall\, k, j, t$$

$$\sum_j [\ell_{t,k,j} - \tau_{t,k} \cdot (e_{t,k,j} - \text{a}_{t,k,j})] = 0, \quad \forall\, k, t. \tag{3}$$

where the budget constraint Eq. (1) defines household consumption and aggregate abatement is $\text{A}_t = \sum_{T=0}^{t} \sum_{k=1}^{N} \sum_{j=1}^{H_{T,k}} \text{a}_{T,k,j}(\tau_{T,k})$ with $\text{a}_{t,k,j}(\tau_{t,k})$ defined by Eq. (2). The parameter ρ is the pure time preference rate.

National redistributional policy determines inequality between households in each country. Thus, transfers ℓ are only formally choices at the global level in Eq. (3) but are determined through the constraints. The resulting level of inequality is anticipated at the global level, which is represented by the constraints f that enter the global objective (together with the budget constraint of the national level). The constraints can be interpreted as defining second-best settings for deriving the carbon tax. While the optimal carbon tax takes into account inequality between and within countries, it does not act as a tool for redistribution beyond how climate change and climate policy affect inequality. In fact, the optimal carbon tax equals zero for the two explicit redistribution schemes we consider in Sections 3.2.1 and 3.2.2 if we set climate damages to zero (see Eqs. (5), (8) and (13)).

The maximization defines the optimal country-specific carbon taxes. The weights w determine the choice on the constrained Pareto frontier. A particular set of weights expresses normative preferences for equity between and within countries at the global level. We do not specify the exact set of welfare weights here but only study the impact of inequality on the SCC for a given set of normative preferences. Generally, normative preferences, i.e. welfare weights, at the global level are based on the principle of "common but differentiated responsibilities" enshrined in the United Nations Framework Convention on Climate Change (UN, 1992). The literature introduced different equity principles that may be used in this context, for example country's historical responsibility for climate change (Kornek et al., 2017), the capacity to conduct large policy projects (Baer et al., 2009) or an equal effort of countries (Tavoni et al., 2013).

The optimal carbon tax calculated below is hence both constrained Pareto-efficient and a normative metric for climate policy that reflects arbitrary global preferences for equity. We explicitly implement discounting as a common form of welfare weighting (Stern, 2008; Anthoff et al., 2009; Anthoff and Emmerling, 2019).

2.2. The SCC as the optimal carbon tax

We build on the concept of the SCC used in previous literature (Azar and Sterner, 1996; Adler et al., 2017; Anthoff and Emmerling, 2019) to allow for inequality within countries in our optimal taxation framework. If our model aggregated households at the national level, the second-best optimal tax rate defined by (3) would be equal to the SCC along the optimal emissions pathway (see Nordhaus 2017; Anthoff and Emmerling 2019). We refer to the optimal tax rates from (3) as the country-specific SCC, also under subnational inequality.

In models with representative agents, the SCC of a country/region is the loss in social welfare from an extra unit of emissions normalized by the gain in social welfare from an additional unit of consumption for the country/region to obtain a monetary measure (Anthoff et al., 2009; Nordhaus, 2014; Adler et al., 2017). In our optimal taxation model, this definition cannot be readily applied to define the SCC because the consumption level of a country $\text{C}_{t,k}$ is not an argument of the SWF, but only the consumption of households. A country's consumption changes indirectly when household consumption changes for different tax levels, and through the resulting redistribution at the national level.

By defining that the SCC equals the second-best optimal tax of each country, we normalize the change in social welfare from an extra unit of emissions by the change in social welfare from consumption that is directly tied to the optimal carbon tax and the resulting national redistribution (possibly including a compensation of damages by national governments). We thereby differ from proposals in Anthoff et al. (2009) and Anthoff and Emmerling (2019) that normalize by the marginal utility of consumption of individuals or by the marginal utility at regional per-capita consumption, respectively. In our optimal taxation model, by contrast, optimal carbon prices and country-specific SCC are directly linked and our SCC is a second-best measure for optimal carbon prices which differs depending on governments' redistributional policies.

Throughout the manuscript, the expressions for the SCC usually include the consumption elasticities of the marginal utilities (we assume that all derivatives exist):

$$\mu_C = -\frac{\frac{d}{dc}\text{muc}}{\text{muc}}(\text{c} - \text{d(A)}) > 0, \mu_{CC} = -\frac{\frac{d}{dc}\text{mucc}}{\text{mucc}}(\text{c} - \text{d}(A)),$$

$$\lambda_C = -\frac{\frac{d}{dc}\text{mua}}{\text{mua}}(\text{c} - \text{d}(A)), \lambda_{CC} = -\frac{\frac{d^2}{dc^2}\text{mua}}{\frac{d}{dc}\text{mua}}(\text{c} - \text{d}(A)).$$

In accordance with the literature (Golosov et al., 2014; Adler et al., 2017; Barrage, 2018), we additionally use the isoelastic utility function as a special case:

$$\text{u}(\text{c} - \text{d}(A), A) = \begin{cases} \frac{(\text{c} - \text{d}(A))^{1-\eta} - 1}{1-\eta} & \eta \neq 1 \\ \log(\text{c} - \text{d}(A)) & \eta = 1 \end{cases} \tag{4}$$

for which the elasticity of marginal felicity is constant at $\mu_C = \eta$ and for which the other elasticities are $\mu_{CC} = \eta + 1$, $\lambda_C = \lambda_{CC} = 0$.

Assuming an isoelastic utility has two advantages. First, we can use estimates of the elasticity of marginal felicity to specify household utility (based on risk aversion or savings data, see Stern (1977); Nordhaus (2014); Groom and Maddison (2018)). Second, the specification focuses on evaluating damages that are either monetary or that can be converted into money-metric by applying consumers' willingness to pay for avoiding non-monetary damages, as in Tol (2002), Hope (2006), Manne and Richels (2005), Nordhaus (2017) and Adler et al. (2017). There is increasing evidence on the value of these types of damages (Burke et al., 2015; Kalkuhl and Wenz, 2020) making SCC estimates more precise.[6]

3. The social cost of carbon with national redistribution

We derive the SCC as the optimal national carbon tax with inequality between and within countries. As a reference case, Sec. 3.1 first determines the SCC if there is no inequality within countries, i.e. with national representative agents. We then continue with the case of inequality within countries. Analysing generic distributional constraints at the national level only permits general conclusions (see App. A.1). We therefore analyze two specific national redistribution schemes that are relevant for climate policy. First, redistribution is nationally optimal and maximizes a national welfare function (Sec. 3.2.1). Second, redistribution is nationally suboptimal because households are not compensated for abatement costs and damages but only reimbursed for what they paid in taxes (Sec. 3.2.2).

The rules for the SCC turn out to be quite complex. To analyze the influence of inequality, we approximate the rules around equality within countries (as in Bernstein et al. (2017), see Appendix A.2). The approximate equations highlight the main drivers of inequality on the SCC, including effects up to the second order. Still the approximations are only valid for small inequalities. Making this assumption is crucial for deriving analytical results and for getting an intuition for the mechanisms driving our model. It is, however, hardly a realistic assumption. To mitigate the concern that our analytical results are driven by this assumption, we additionally perform numerical simulations with real-world inequalities in Sec. 4.2.

To compare the rules under household inequality with the SCC given in the representative agent case, we approximate marginal benefits from abatement and marginal utility of consumption separately. The results include the standard deviations of household characteristics and the covariances between them. Standard deviations introduce inequality at the household level for each characteristic like income or damages from climate change. Covariances describe whether the effects of inequality of two different characteristics cancel or reinforce each other.

3.1. The SCC for the representative agent case

This section derives the SCC when there is a representative agent in each country, allowing for inequality between countries. In this case, the households in each country are equal. We thus refer to the representative agent as the equality case below. The

[6] In the literature that uses the isoelastic function, it is common practice to combine monetary and non-monetary damages into one damage function that is applied to the production function, with the DICE model as the most prominent example (Nordhaus, 2014). Our results can be compared to this literature in the following sense. When we use the isoelastic utility function, additive damages $d(A)$ can be interpreted as representing monetized damages that combine monetary and non-market damages, where the latter is converted with a willingness to pay for the environment that is assumed to be constant for each individual. We point the interested reader to literature that disentangles both types of damages in numerical integrated assessment of climate policy and discusses the functional form of damages (Weitzman, 2010; Barrage, 2020; Drupp and Hänsel, 2020).

SCC with representative agents serves as a benchmark when the next two sections introduce inequality at the household level.

We set all household characteristics equal to the country mean: $c_{t,k,j} = \frac{1}{H_{t,k}}\sum_j (i_{t,k,j} - m_{t,k,j}(a_{t,k,j}) + \ell_{t,k,j} - \tau_{t,k}(e_{t,k,j} - a_{t,k,j})) = \bar{i}_{t,k} - \bar{m}_{t,k} = \bar{c}_{t,k}$ and $d_{t,k,j}(A_t) = \frac{1}{H_{t,k}}\sum_j d_{t,k,j}(A_t) = \bar{d}_{t,k}(A_t)$. The mean welfare weight of each household is $\bar{w}_{t,k} = 1/H_{t,k}\sum_j w_{t,k,j}$. The maximization at the global level becomes:

$$\max_{\tau_{t,k}} \sum_{T=0}^{t_{\text{end}}} \frac{1}{(1+\rho)^T} \sum_k H_{T,k}\bar{w}_{T,k} \cdot u(\bar{c}_{T,k} - \bar{d}_{T,k}, g_{T,k}(A_T))$$

where aggregate abatement is $A_t = \sum_{T=0}^{t} \sum_{k=1}^{N} \sum_{j=1}^{H_{T,k}} a_{T,k,j}$ with $a_{t,k,j}(\tau_{t,k})$ defined by Eq. (2).

Solving the optimization yields the country-specific SCC under equality within countries. Each country p's SCC is:

$$\tau_{t,p}|_{\text{EQ}} = \frac{\sum_{T=t}^{t_{\text{end}}} \frac{1}{(1+\rho)^{T-t}} \sum_k H_{T,k}\bar{w}_{T,k} \left\{ \text{muc}_{T,k} \cdot (-\bar{d}'_{T,k}) + \text{mua}_{T,k} \right\}}{\bar{w}_{t,p}\text{muc}_{t,p}}. \tag{5}$$

Here, $\text{muc}_{T,k}$ and $\text{mua}_{T,k}$ indicate the value of the functions at the mean composite consumption of each county $\bar{c}_{T,k} - \bar{d}_{T,k}$. Marginal damages are $\bar{d}'_{T,k} = \partial\bar{d}_{T,k}(A_T)/\partial A_T$. The set of mean welfare weights $\bar{w}_{t,k}$ determines global preferences for equity between countries. Eq. (5) spells out the SCC for representative agents in terms of our model.

The SCC is the optimal carbon tax. The rule for the SCC reflects the optimality condition, in which marginal benefits of an additional unit of abatement are equal to marginal costs of providing extra abatement in each country, both evaluated with the global social welfare function. The SCC depends on inequality between countries and on normative preferences at the global level.

To see this, consider marginal benefits. They consist of two parts. First avoided damages add to the consumption of households. At the global level, this change in composite consumption is evaluated with the change in social welfare of that household, which is the weighted marginal utility of consumption of the country this household lives in. Avoided damages tend to have a higher social value in low-income countries because their marginal utility of consumption is higher. A lower welfare weight can offset this effect. Second, marginal benefits include the increase in utility from non-market benefits. The social value of non-market benefits is larger in lower-income countries if $\lambda_C > 0$ and larger in higher-income countries if $\lambda_C < 0$, again if not offset by the welfare weight.

Providing an additional unit of abatement tends to be socially more costly in lower-income countries, again because their marginal utility of consumption is higher. Indeed, Eq. (5) shows that lower-income countries will have a lower SCC if their welfare weight is high enough. If weights tend towards equality between countries, optimal climate policy establishes an implicit redistribution from high-to low-income countries through lower abatement efforts for low-income countries, which benefit from higher abatement by high-income countries (see also Chichilnisky and Heal, 1994; Anthoff et al., 2009; Adler et al., 2017; Budolfson and Dennig, 2020).

However, the SCC is the same for all countries if the existing level of inequality among countries is globally preferred and Negishi-weights are chosen (Chichilnisky and Heal, 1994; Nordhaus and Yang, 1996). Lower-income countries receive a lower weight that is inversely proportional to their marginal utility of consumption. Negishi weights offset the influence of inequality within countries at each point in time within the social welfare function, but their use has been criticized as they may distort intertemporal preferences (Dennig and Emmerling, 2017).

We next analyze how the SCC changes under inequality within countries.

3.2. *The SCC for inequality within countries*

This section introduces inequality between households in each country, which is determined by the national governance level. Modeling this implies adding constraints on redistribution between households (f) to the maximization at the global level. We find two effects that govern why the SCC changes under inequality within countries. We introduce both effects now and refer to them throughout the rest of the analysis.

First, the social value of an extra unit of consumption and of abatement differs from its respective level at equality. For equal welfare weights, Fig. 1 illustrates this effect by showing the marginal utility of consumption on the left and of abatement on the right hand side. Whether the social value increases or decreases depends on whether the marginal utility functions are convex or concave. The left hand side illustrates the convex case exemplary for the marginal utility of consumption. The isoelastic utility function leads to this shape of marginal utility of consumption. An extra unit of consumption to two identical households each is socially less valuable than an extra unit of consumption to a high- and a low-income household each, holding aggregate consumption fixed. The opposite effect occurs if marginal utility of consumption is concave, a case that can occur for our general utility function (discussed more in App. A.5). The right hand side of Fig. 1 shows the opposite effect exemplary for the marginal utility of abatement: the social value of an extra unit of abatement in non-market benefits decreases under inequality between households.

Second, the SCC influences inequality within countries. For a given set of SCC, the national level redistributes according to the constraints f in response to the carbon taxes. Fig. 2 illustrates the case when the national level neutralizes disproportionate

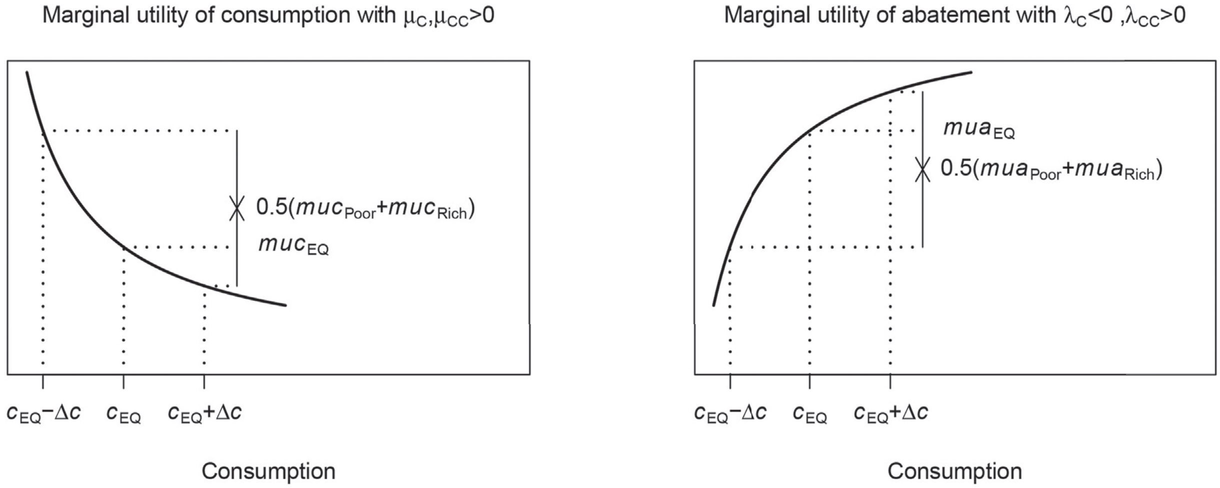

Fig. 1. Marginal utility of consumption (left) and of abatement (right) of two households. Under inequality, the sum of marginal utilities of consumption (abatement) is larger (smaller) compared to the equality case. The function muc changes from convex (in the figure) to concave if $\mu_{CC} < 0$. The function mua is also concave (as in the figure) if $\lambda_C > 0$ and $\lambda_{CC} < 0$; it is convex if both elasticities have the same sign.

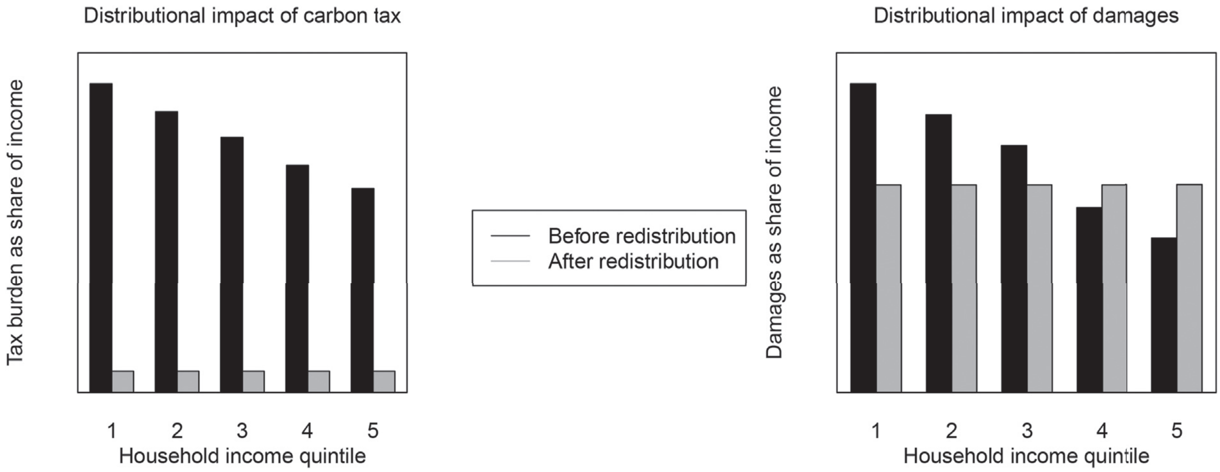

Fig. 2. Sum of abatement cost and carbon tax payments (left) and damages (right) as a share of income across income quintiles, before and after transfers and for a given set of SCC. The "Before redistribution" scenario is the hypothetical case where carbon tax revenues have not been recycled to quintiles and no other compensation has been implemented. The "After redistribution" scenario assumes that the national level adjusts redistribution between households and recycles revenues to offset the regressive distributional impact of the tax and to offset higher damages to low-income households. Note that the incidence can be regressive, neutral or progressive, depending on the country (Sterner, 2011; Dorband et al., 2019).

damages and carbon tax burdens on low-income households, the scenario of nationally optimal transfers studied in Sec. 3.2.1. The left hand side of Fig. 2 shows a case where the distributional burden of carbon tax is regressive in the sum of abatement costs and tax payments as a share of income (black). The national level redistributes the tax revenue to render the carbon tax incidence neutral (grey). On the right hand side of Fig. 2, damages fall disproportionately on low-income households before redistribution (black). In this example of national transfers, damages are proportional to income after redistribution (grey). Whether the national level neutralizes climate and policy effects fully, partially or not at all is anticipated at the global level and influences the SCC.

Next, we show how the two effects lead to an SCC that differs from the equality case.

3.2.1. Endogenous redistribution: nationally optimal transfers

In the first scheme, the national level chooses transfers to maximize a national welfare function. The main result shows that in this case the SCC hardly deviates from the equality case if two conditions are fulfilled: the utility is isoelastic and the elasticity of marginal felicity η (see Eq. (4)) is close to unity. The SCC does not change even if inequality within countries is large and preferences at the global level would demand transfers to completely offset this inequality.

The national welfare function (NWF) aggregates the utilities of households through a weighted sum, where $z_{t,k,j} > 0$ are the welfare weights the national level assigns to each household. Transfers redistribute between households at each point in time, so that the objective of each country k for each period t is:

$$\max_{\ell_{t,k,s}} \mathrm{NWF} = \sum_{j}^{H_{t,k}} z_{t,k,j} \cdot \mathrm{u}(\mathrm{c}_{t,k,j} - \mathrm{d}_{t,k,j}, \mathrm{g}_{t,k}(\mathrm{A}_t))$$

$$\text{s.t.} \quad \sum_j \ell_{t,k,j} = \tau_{t,k} \sum_j (e_{t,k,j} - \mathrm{a}_{t,k,j}(\tau_{t,k})),$$

$$c_{t,k,j} - d_{t,k,j} > 0 \; \forall \; t, k, j.$$

Without loss of generality, we assume that average national welfare weights are one for each country ($\overline{z}_{t,k} = 1$). Carbon taxes τ are exogenous parameters in the optimization of national governments. The budget constraint (1) defines household consumption.

National institutions redistribute between households based on their preferences for equity, where more than the carbon tax revenue may be used to redistribute optimally. The national weights mimic the tax and welfare system within each country. The resulting redistribution compensates households for damages and costs but leaves a certain level of inequality, for example based on household's income differences.

To keep the analysis tractable, we assume that the national optimization has an interior solution. At the optimum, transfers equalize weighted marginal utilities of consumption between households in each country.[7] The constraints that determine national redistribution are:

$$\mathrm{f}_{t,k,j}(\ell_{t,k,j}, \mathrm{A}_t, \tau_{t,k}) = z_{t,k,j}\mathrm{muc}_{t,k,j} - z_{t,k,s}\mathrm{muc}_{t,k,s} = 0. \tag{7}$$

The weights z determine – together with the utility function – each household's composite consumption relative to all other households.

At the global level, the SCC is determined anticipating national redistribution. Accounting for Eq. (7) as constraints in (3) yields the SCC under nationally optimal transfers for each country p and time t (for details see Appendix A.3):

$$\tau_{t,p}|_{\mathrm{NaOp}} = \frac{\sum_{T=t}^{t_{\mathrm{end}}} \frac{1}{(1+\rho)^{T-t}} \sum_{k,j} \left[\kappa_{T,k} \cdot (-\overline{\mathrm{d}}'_{T,k}) + w_{T,k,j}\mathrm{mua}_{T,k,j} - \left(w_{T,k,j}\mathrm{muc}_{T,k,j} - \kappa_{T,k} \right) \frac{\mathrm{muac}_{T,k,j}}{\mathrm{mucc}_{T,k,j}} \right]}{\kappa_{t,p}}. \tag{8}$$

with

$$\kappa_{t,p} = \frac{\sum_j \frac{w_{t,p,j}\mathrm{muc}_{t,p,j}}{z_{t,p,j}\mathrm{mucc}_{t,p,j}}}{\sum_j \frac{1}{z_{t,p,j}\mathrm{mucc}_{t,p,j}}}, \quad \forall \; p, t \tag{9}$$

where $\mathrm{muac}_{T,k,j} = \frac{\partial}{\partial \mathrm{c}_{T,k,j}} \mathrm{mua}_{T,k,j}$ are the cross derivatives.

The rule for the SCC depends on how monetary damages and abatement costs influence a household's composite consumption. The SCC aggregates avoided damages and uses the normalization given in Eq. (9). The normalization $\kappa_{t,p}$ captures the value of an additional unit of composite consumption in each country. The value is determined by how national institutions redistribute additional consumption, which follows Eq. (7). Thus, $\kappa_{t,p}$ depends on the change of marginal utilities of consumption and the national welfare weights as these determine how national institutions redistribute at the margin. The value at the global level is represented through global welfare weights and marginal utilities of consumption of households.

The SCC adds non-monetary benefits to avoided damages through the marginal utility of abatement. Due to national transfers, an additional term comes in if muac $\neq 0$. The additional term captures how benefits of abatement influence household utility and thus how these benefits interact with the distributive motive at the national level.

It is hard to draw further conclusions about how the SCC is influenced by subnational inequality from Eq. (8). We thus make simplifying assumptions to gain further insights. Our first result shows that for the special case of logarithmic utility, the SCC

[7] The Lagrangian to the national maximization problem is:

$$\boldsymbol{\mathcal{L}} = \sum_t \sum_{k,j} z_{t,k,j} \cdot \mathrm{u}(\mathrm{c}_{t,k,j} - \mathrm{d}_{t,k,j}, \mathrm{g}_{t,k}(\mathrm{A}_t)) - \epsilon_{t,k} \left(\sum_j \ell_{t,k,j} - \tau_{t,k} \sum_j (e_{t,k,j} - \mathrm{a}_{t,k,j}) \right).$$

Setting $\partial\boldsymbol{\mathcal{L}}/\partial\ell_{t,k,j} = 0$ we get the following first-order condition:

$$\epsilon_{t,k} = z_{t,k,j}\mathrm{muc}_{t,k,j} \quad \forall \; j. \tag{6}$$

By choosing an arbitrary household of each country s, Eq. (6) leads to Eq. (7).

under inequality within countries does not change compared to the equality case.

Proposition 1. *For nationally optimal transfers the SCC does not change compared to equality within countries if utility is logarithmic* ($\eta = 1$).

Proof. *We insert the isoelastic utility function with* $\eta = 1$ *in* Eq. (8). *With that we have*: mua, muac $= 0$, $\text{muc}_{t,p,j} = (c_{t,p,j} - d_{t,p,j})^{-1}$, $\text{mucc}_{t,p,j} = -(c_{t,p,j} - d_{t,p,j})^{-2}$. Eq. (8) *becomes*:

$$\tau_{t,p}|_{\text{NaOp}} = \frac{1}{\kappa_{t,p}} \sum_{T=t}^{t_{\text{end}}} \frac{1}{(1+\rho)^{T-t}} \sum_{k,j} \kappa_{T,k} \cdot (-\overline{\text{d}}'_{T,k}).$$

For nationally optimal transfers we know $\text{z}_{\text{t,p,j}}/(\text{c}_{\text{t,p,j}} - \text{d}_{\text{t,p,j}}) = \epsilon_{\text{t,p}}$ (Eq. (6)). Eq. (9) becomes:

$$\kappa_{t,p} = \frac{\sum_j \frac{w_{t,p,j}\cdot(c_{t,p,j}-d_{t,p,j})}{z_{t,p,j}}}{\sum_j \frac{(c_{t,p,j}-d_{t,p,j})^2}{z_{t,p,j}}} = \frac{\sum_j \frac{w_{t,p,j}}{\epsilon_{t,p}}}{\sum_j \frac{(c_{t,p,j}-d_{t,p,j})}{\epsilon_{t,p}}} = \frac{\overline{w}_{t,p}}{\overline{c}_{t,p} - \overline{d}_{t,p}}.$$

Hence $\kappa_{\text{t,p}}$ is equal to $\overline{w}_{t,p}\text{muc}_{t,p}$. Inserting, the rule for the SCC becomes

$$\tau_{t,p}|_{\text{NaOp}} = \frac{\sum_{T=t}^{t_{\text{end}}} \frac{1}{(1+\rho)^{T-t}} \sum_k \text{H}_{T,k}\overline{w}_{T,k}\text{muc}_{T,k} \cdot (-\overline{\text{d}}'_{T,k})}{\sum_j \overline{w}_{t,p}\text{muc}_{t,p}}.$$

which is equal to the SCC under equality in Eq. (5) for logarithmic utility. □

The intuition behind this somewhat surprising result is that the two effects identified in Figs. 1 and 2 directly offset each other. Inequality between households changes the social value of increasing consumption (the effect visualized in Fig. 1) but national distributional policy allocates different levels of consumption to households (the effect visualized in Fig. 2).

Explicitly, the national level redistributes until each household consumes a share of total national composite consumption that is proportional to its welfare weight: $\text{c}_{t,k,j} - \text{d}_{t,k,j} = \frac{z_{t,k,j}}{H_{t,k}}(\text{C}_{t,k} - \text{D}_{t,k})$.[8] At the global level, adjusting the SCC changes national composite consumption. Through redistribution, utility of each household changes in the following way:

$$\text{du}(\text{c}_{t,k,j} - \text{d}_{t,k,j}) = \frac{\text{d}(\text{c}_{t,k,j} - \text{d}_{t,k,j})}{\text{c}_{t,k,j} - \text{d}_{t,k,j}} = \frac{\frac{z_{t,k,j}}{H_{t,k}}\text{d}(\text{C}_{t,k} - \text{D}_{t,k})}{\frac{z_{t,k,j}}{H_{t,k}}(\text{C}_{t,k} - \text{D}_{t,k})} = \frac{\text{d}(\overline{\text{c}}_{t,k} - \overline{\text{d}}_{t,k})}{\overline{\text{c}}_{t,k} - \overline{\text{d}}_{t,k}} = \text{du}(\overline{\text{c}}_{t,k} - \overline{\text{d}}_{t,k})$$

Hence, each household's utility changes as if all households were equal. The SCC does not change under inequality within countries.

We next show how the SCC changes under inequality for general utility functions. To that end, we approximate the rule for the SCC for small inequalities. The results therefore only present main drivers of inequality. The next lemma demonstrates that the SCC depends on (i) the shape of the utility function with elasticities μ and λ; (ii) inequality within countries, approximated by standard deviations of national welfare weights $\sigma_{t,k}(z)$ of country k and time t; (iii) how national and global weights differ, approximated by the covariance between the weights $\text{cov}_{t,k}(w,z)$.

Lemma 1. *For nationally optimal transfers the SCC*

(a) is for each country p and time t approximated by:

$$\tau_{t,p}|_{\text{NaOp}} \approx \frac{\sum_{T=t}^{t_{\text{end}}} \frac{1}{(1+\rho)^{T-t}} \sum_k H_{T,k}\overline{w}_{T,k}\text{muc}_{T,k} \cdot (-\overline{\text{d}}'_{T,k}) \left[1 + \phi_{T,k}\right]}{\overline{w}_{t,p}\text{muc}_{t,p}\left[1 + \phi_{t,p}\right]} \tag{11}$$

if utility is isoelastic. The adjustment factors ϕ determine the change of the SCC compared to equality within countries and are given by:

$$\phi_{t,k} = \left(\sigma^2_{t,k}(z) - 2\frac{\text{cov}_{t,k}(w,z)}{\overline{w}_{t,k}}\right)\frac{1}{2}\frac{\eta - 1}{\eta} \quad \forall\, k, t.$$

[8] This can be derived by rearranging Eq. (6) to $\text{c}_{t,k,j} - \text{d}_{t,k,j} = (z_{t,k,j})^{1/\eta}(\varepsilon_{t,k})^{-1/\eta}$. Summing over j yields $\text{C}_{t,k} - \text{D}_{t,k} = \sum_s (z_{t,k,s})^{1/\eta}(\varepsilon_{t,k})^{-1/\eta}$. Solving the last equation for $(\varepsilon_{t,k})^{-1/\eta}$ and inserting yields:

$$\text{c}_{t,k,j} - \text{d}_{t,k,j} = \frac{(z_{t,k,j})^{1/\eta}}{\sum_s (z_{t,k,s})^{1/\eta}}(\text{C}_{t,k} - \text{D}_{t,k}) \tag{10}$$

If equality is preferred at the global level ($w_{t,k,j} = \overline{w}_{t,k}$), the SCC at time t tends to increase for the country with the smallest inequality – i.e. the smallest $\sigma^2_{t,p}(z)$ – if $\eta > 1$ and decrease if $\eta < 1$. For the country with the largest inequality the reverse holds.

(b) is for each country p and time t generally approximated by:

$$\tau_{t,p}|_{\text{NaOp}} \approx \frac{\sum_{T=t}^{t_{\text{end}}} \frac{1}{(1+\rho)^{T-t}} \sum_k H_{T,k}\overline{w}_{T,k} \left\{ \text{muc}_{T,k} \cdot (-\overline{\text{d}}'_{T,k}) \left[1+\phi_{T,k}\right] + \text{mua}_{T,k}\left[1+\varphi_{T,k}\right] \right\}}{\overline{w}_{t,p}\text{muc}_{t,p}\left\{1+\phi_{t,p}\right\}}. \tag{12}$$

The adjustment factors ϕ and φ are given by:

$$\phi_{t,k} = \left(\sigma^2_{t,k}(z) - 2\frac{\text{cov}_{t,k}(w,z)}{\overline{w}_{t,k}}\right)\left(1 - \frac{1}{2}\frac{(\mu_{CC})_{t,k}}{(\mu_C)_{t,k}}\right) \quad \forall\, k,t$$

$$\varphi_{t,k} = \left(\sigma^2_{t,k}(z) - 2\frac{\text{cov}_{t,k}(w,z)}{\overline{w}_{t,k}}\right)\frac{(\lambda_C)_{t,k}}{(\mu_C)_{t,k}}\left(1 - \frac{1}{2}\frac{(\lambda_{CC})_{t,k}}{(\mu_C)_{t,k}}\right) \quad \forall\, k,t.$$

Here, $\text{muc}_{t,k}$ and $\text{mua}_{t,k}$ as well as $(\mu_C)_{t,k}$, $(\mu_{CC})_{t,k}$, $(\lambda_C)_{t,k}$, $(\lambda_{CC})_{t,k}$ indicate the value of the functions at the national mean $\overline{\text{c}}_{t,k} - \overline{\text{d}}_{t,k}$.

Proof. *The equations are derived by applying a second-order Taylor approximation in the variables* $(w_{t,k,1}, \ldots, w_{t,k,H_{t,k}}, z_{t,k,1}, \ldots, z_{t,k,H_{k,t}})\ \forall\, k,t$ *to the numerator and denominator in* Eq. (8). *We detail the proof in App. A.4.* □

For the isoelastic utility function, the overall effect of inequality on the SCC switches sign with $\eta \lessgtr 1$, Lemma 1 (a). As for logarithmic utility, the effects visualized in Figs. 1 and 2 still offset each other, but not completely. To isolate how the shape of the utility function influences the SCC from effects resulting from global preferences for equity, consider the case where equality is preferred at the global level ($w_{t,k,j} = \overline{w}_{t,k}$). As for logarithmic utility, the national level allocates a fixed share of total composite consumption to households that is proportional to their national welfare weight, see Footnote 8. If $\eta > 1$, low-consumption households have a disproportionate larger gain in utility from an additional unit of consumption. Allocating a small share of consumption to low-consumption households is beneficial if equality is preferred at the global level. Indeed, Lemma 1 shows that the SCC for the country with the largest inequality tends to decrease if $\eta > 1$. The SCC tends to increase for the country with the lowest inequality. As a result, the low-consumption households in the more unequal countries have larger composite consumption through the abatement efforts of the other countries while saving abatement costs. For $\eta < 1$ the opposite holds. Here, the utility of low-consumption households increases to a lesser extent with consumption so that the small increase in their composite consumption (allocated from the national level) is globally less preferable.

In short, the SCC influences aggregate consumption levels between countries. Aggregate consumption in turn influences subnational inequality as national institutions redistribute optimally. Different SCCs compared to the equality case are used at the global level to avoid climate change while mitigating inequality between and within countries according to the social welfare function.

Preferences for equity at the global level that align with the national level offset the effect of inequality on the SCC. In Eq. (11), positive covariances between national and global welfare weights capture how the level of inequality that is implemented by national transfers is actually preferred at the global level. If global welfare weights are proportional to Negishi weights at each point in time, the influence of inequality within countries disappears and the SCC equals aggregate marginal damages that are intertemporally aggregated.[9]

The intuition is more complex in case of general utility functions. We only briefly discuss it here, leaving the detailed explanation of all effects to Appendix A.5. The SCC in Lemma 1 (b) shows that it is again the shape of the utility function that determines differences to the case of equality in Eq. (5). The adjustment factors ϕ and φ capture the differences. The factors combine the two effects visualized in Figs. 1 and 2. The consumption elasticities (μ_C in combination with μ_{CC} and λ_C in combination with λ_{CC}) enter the adjustment factors because they determine how the social value of increasing consumption and abatement changes under inequality between households (the effect visualized in Fig. 1). The elasticities also determine how the national level redistributes between households (the effect visualized in Fig. 2). Notably, for general utility functions the stock of abatement additionally affects the utility of households in non-market benefits. The national level equalizes weighted marginal utilities of consumption, and their level depends on the stock of abatement for general functional forms. The elasticities of the marginal utility of abatement (λ_C and λ_{CC}) determine how the stock of abatement influences marginal utilities of consumption. For example, a low-income household's marginal utility of consumption might decrease with a worse climate as they are less able to enjoy their lunch at higher temperatures. This effect in turn influences the decision to redistribute at the national level: more

[9] Negishi weights are inversely proportional to the marginal utility of consumption: $w_{t,k,j} = B_t/\text{muc}_{t,k,j}$ with a normalization parameter B_t (Chichilnisky and Heal, 1994; Nordhaus and Yang, 1996). Inserting this relationship in Eqs. (8) and (9) yields $\tau_{t,p} = \sum_{T=t}^{t_{\text{end}}} \frac{1}{(1+\rho)^{T-t}} \sum_k H_{T,k} \cdot (-\overline{\text{d}}'_{T,k}) B_T/B_t$ for the isoelastic utility function. The approximation in Eq. (11) yields the same SCC when applying a second-order Taylor approximation of the global weights $w_{t,k,j} = B_t/\text{muc}_{t,k,j}$ in the national weights $z_{t,k,j}$ and inserting in (11). The approximation of w requires the relationships (A.3) and (A.6) from the appendix.

compensation for households might be warranted, depending on the corresponding change in marginal utility of high-income households. The elasticities λ_C and λ_{CC} therefore also affect national redistribution, and enter the rule for the SCC in Lemma 1 (b).

Our results thus far rely on national institutions reaching each household and having the necessary resources available to compensate. The next section shows that the outcome critically changes when national institutions do not or cannot compensate households for climate damages.

3.2.2. Exogenous redistribution: nationally suboptimal transfers

Under the second scheme, households are reimbursed exactly the amount they paid in carbon taxes. In general, transfers are nationally suboptimal as households have to bear the costs of abatement and of residual climate change but are not compensated for them. This second-best allocation models a situation, in which national institutions fail to account for the distributional consequences of climate policy. As a consequence, distributional and climate policies interact: We show that if climate damages accrue disproportionately to low-income households in one country, the SCC tends to increase for every country.

The national distributional constraints are: $\mathrm{f}_{t,k,j} = \ell_{t,k,j} - \tau_{t,k} \cdot (e_{t,k,j} - \mathrm{a}_{t,k,j}) = 0$. The optimization in Eq. (3) with these constraints leads to the following SCC for each country p (for details see the online appendix):

$$\tau_{t,p}|_{\text{NaSuOp}} = \frac{\sum_{T=t}^{t_{\text{end}}} \frac{1}{(1+\rho)^{T-t}} \sum\limits_{k,j} w_{T,k,j} \left\{ \mathrm{muc}_{T,k,j} \cdot (-\mathrm{d}'_{T,k,j}) + \mathrm{mua}_{T,k,j} \right\}}{\sum\limits_{j} w_{t,p,j} \mathrm{muc}_{t,p,j} \frac{\frac{\partial \mathrm{a}_{t,p,j}}{\partial \tau_{t,p}}}{\sum_s \frac{\partial \mathrm{a}_{t,p,s}}{\partial \tau_{t,p}}}}. \tag{13}$$

In Eq. (13), the numerator aggregates marginal benefits of an extra unit of abatement across all households, evaluated with the social welfare function. Thus, our rule for the SCC is similar to Anthoff and Emmerling (2019, Eq. (12)) for a different social welfare function. We deviate from Anthoff and Emmerling by taking into account that an additional unit of abatement is provided by carbon taxes with the national level reimbursing tax payments. Thus, the denominator in the rule for the SCC reflects mitigation costs across households through a weighted average of marginal utilities of consumption of the households in each country.

The rule for the SCC looks similar as in the equality case in Eq. (5). The SCC can however be quite different in magnitude under inequality. To see this we make inequality at the household level more explicit and assume that households' costs of abatement are proportional to income:[10]

$$\mathrm{m}_{t,k,j}(\mathrm{a}_{t,k,j}) = \frac{i_{t,k,j}}{\bar{i}_{t,k}} \overline{\mathrm{m}}_{t,k}(\tau_{t,k}).$$

Mean national abatement costs are $\overline{\mathrm{m}}_{t,k}(\tau_{t,k}) = \frac{1}{H_{t,k}} \sum_j \mathrm{m}_{t,k,j}(\mathrm{a}_{t,k,j})$, which are a function of the carbon tax through Eq. (2).

We allow damages to deviate from proportionality to income

$$\mathrm{d}_{t,k,j}(\mathrm{A}_t) = \left(\frac{i_{t,k,j}}{\bar{i}_{t,k}} + \delta_{t,k,j} \right) \cdot \overline{\mathrm{d}}_{t,k}(\mathrm{A}_t).$$

$\delta_{t,k,j}$ has a zero mean in each country. If $\delta = 0$, damages are proportional to income. In this case, the income elasticity of damages is 1. On average, damages accrue disproportionately to low-income households if δ is negatively correlated with income i. In the numerical application in Sec. 4.2, the covariance between δ and income is negative whenever the income elasticity of damages is below 1.

Composite consumption of each household is:

$$\mathrm{c}_{t,k,j} - \mathrm{d}_{t,k,j}(\mathrm{A}_t) = i_{t,k,j} - \frac{i_{t,k,j}}{\bar{i}_{t,k}} \overline{\mathrm{m}}_{t,k}(\tau_{t,k}) - \left(\frac{i_{t,k,j}}{\bar{i}_{t,k}} + \delta_{t,k,j} \right) \overline{\mathrm{d}}_{t,k}(\mathrm{A}_t). \tag{14}$$

The next proposition derives the SCC when damages and abatement costs are directly proportional to income (i.e. $\delta = 0$) and utility is logarithmic. We again observe for this special case that the SCC is equal to the equality case.

Proposition 2. *If abatement costs and damages are directly proportional to income and national governments reimburse households exactly what they paid in taxes, the SCC does not change compared to equality within countries if utility is logarithmic* ($\eta = 1$).

Proof. *First note that for the isoelastic utility, we have* mua $= 0$. *App. A.6 further shows that with* $\delta_{t,k,j} = 0$ *and proportional abatement costs* Eq. (13) *can be simplified to*:

[10] Although the literature on the carbon policy incidence often finds regressive effects, i.e. policy costs disproportionately affect low-income groups (Parry et al., 2007), a proportional effect is a good first-order assumption and has been used in previous literature (Dennig et al., 2015).

$$\tau_{t,p}|_{\text{NaSuOp}} = \frac{\sum_{T=t}^{t_{\text{end}}} \frac{1}{(1+\rho)^{T-t}} \sum_{k,j} w_{T,k,j} \text{muc}_{T,k,j} \cdot (-\overline{\text{d}}'_{T,k}) \frac{\text{i}_{T,k,j}}{\overline{\text{i}}_{T,k}}}{\sum_{j} w_{t,p,j} \text{muc}_{t,p,j} \frac{\text{i}_{t,p,j}}{\text{H}_{t,p}\overline{\text{i}}_{t,p}}}.$$

Using $\eta = 1$ and applying proportionality yields $\text{muc}_{t,k,j} = \frac{1}{\text{c}_{t,k,j}-\text{d}_{t,k,j}} = \frac{1}{\frac{\text{i}_{t,k,j}}{\overline{\text{i}}_{t,k}}(\overline{\text{i}}_{t,k}-\overline{\text{m}}_{t,k}-\overline{\text{d}}_{t,k})}$. Hence, $\text{muc}_{t,k,j}\frac{\text{i}_{t,k,j}}{\overline{\text{i}}_{t,k}} = \text{muc}_{t,k}, \forall t,k,j$ with $\eta = 1$. Inserting, the SCC becomes:

$$\tau_{t,p}|_{\text{NaSuOp}} = \frac{\sum_{T=t}^{t_{\text{end}}} \frac{1}{(1+\rho)^{T-t}} \sum_{k} \text{H}_{T,k} \overline{w}_{T,k} \text{muc}_{T,k} \cdot (-\overline{\text{d}}'_{T,k})}{\sum_{j} \overline{w}_{t,p} \text{muc}_{t,p}}.$$

which is equal to the SCC under equality in Eq. (5) for logarithmic utility. □

The results in Props. 1 and 2 are the same. In both cases, consumption of households is a fixed share of total composite consumption of their country. Hence, the same reasoning as in Prop. 1 is valid in this case. Anthoff and Emmerling (2019) retrieve a related result for the case of a different social welfare function.

The next lemma shows that if utility diverges from the logarithmic case, the SCC may again decrease or increase if damages are proportional to income. The approximated SCC depends on the standard deviation in income $\sigma_{t,k}(i)$ and the covariance $\text{cov}_{t,k}(w,i)$ of global welfare weights and income of households. As we rely on approximations, the results only present main drivers of inequality.

Lemma 2. *If abatement costs and damages are directly proportional to income and national governments reimburse households exactly what they paid in taxes, the SCC*

(a) is for each country p and time t approximated by:

$$\tau_{t,p}|_{\text{NaSuOpA}} \approx \frac{\sum_{T=t}^{t_{\text{end}}} \frac{1}{(1+\rho)^{T-t}} \sum_{k=1}^{N} H_{T,k} \overline{w}_{T,k} \text{muc}_{T,k} \cdot (-\overline{\text{d}}'_{T,k}) \left\{1 + \widetilde{\phi}_{T,k}\right\}}{\overline{w}_{t,p} \text{muc}_{t,p} \left\{1 + \widetilde{\phi}_{t,p}\right\}} \tag{15}$$

if utility is isoelastic. The adjustment factors $\widetilde{\phi}$ determine the change of the SCC compared to equality within countries and are given by:

$$\widetilde{\phi}_{t,p} = (\eta - 1)\left(\frac{\eta}{2}\frac{\sigma^2_{t,p}(i)}{(\overline{i}_{t,p})^2} - \frac{\text{cov}_{t,p}(w,i)}{\overline{w}_{t,p}\overline{i}_{t,p}}\right) \quad \forall\, p, t.$$

If equality is preferred at the global level ($w_{t,k,j} = \overline{w}_{t,k}$), the SCC tends to increase compared to equality for the country with the smallest income inequality at time t, i.e. smallest $\frac{\sigma^2_{t,p}(i)}{(\overline{i}_{t,p})^2}$, if $\eta > 1$ and to decrease if $\eta < 1$. For the country with the largest inequality the same holds vice versa.

(b) is for each country p and time t generally approximated by:

$$\tau_{t,p}|_{\text{NaSuOpA}} \approx \frac{\sum_{T=t}^{t_{\text{end}}} \frac{1}{(1+\rho)^{T-t}} \sum_{k=1}^{N} H_{T,k} \overline{w}_{T,k} \left[\text{muc}_{T,k} \cdot (-\overline{\text{d}}'_{T,k}) \left\{1 + \widetilde{\phi}_{T,k}\right\} + \text{mua}_{T,k}\left\{1 + \widetilde{\varphi}_{T,k}\right\}\right]}{\overline{w}_{t,p} \text{muc}_{t,p} \left\{1 + \widetilde{\phi}_{t,p}\right\}}, \tag{16}$$

The adjustment factors $\widetilde{\phi}$ *and* $\widetilde{\varphi}$ *are given by*:

$$\widetilde{\phi}_{t,k} = \left(-2 + (\mu_{CC})_{t,k}\right)(\mu_C)_{t,k}\frac{\frac{1}{2}\sigma^2_{t,k}(i)}{(\overline{i}_{t,k})^2} + \left(1 - (\mu_C)_{t,k}\right)\frac{\text{cov}_{t,k}(w,i)}{\overline{w}_{t,k}\overline{i}_{t,k}} \quad \forall\, k, t$$

$$\widetilde{\varphi}_{t,k} = \frac{1}{2}(\lambda_C)_{t,k}(\lambda_{CC})_{t,k}\frac{\sigma^2_{t,k}(i)}{(\overline{i}_{t,k})^2} - (\lambda_C)_{t,k}\frac{\text{cov}_{t,k}(w,i)}{\overline{w}_{t,k}\overline{i}_{t,k}} \quad \forall\, k, t.$$

Proof. *The Lemma is derived by applying a second-order Taylor approximation in the variables* $(w_{t,k,1}, \ldots, w_{t,k,H_{t,k}}, i_{t,k,1}, \ldots, i_{t,k,H_{t,k}})\ \forall\, k, t$ *to the numerator and denominator in Eq.* (13)*. We detail the proof in App. A.6.* □

The Lemma shows that the SCC of each country depends on the level of inequality in all countries. As for nationally optimal transfers, no clear-cut conclusion is generally possible on how the SCC depends on within-country inequality.

In fact, the result for isoelastic utility functions are the same in Lemmas 1 and 2. For this functional form, consumption of households is a fixed share of total composite consumption of their country as in the case of nationally optimal transfers.[11] Again, the same reasoning as in Lemma 1 is valid also for nationally suboptimal transfers. The SCC hardly deviates from the case of equality if utility is approximately logarithmic.

The effects of inequality for general utility functions as analyzed in Lemma 2 (b) are more complex. First, the SCC influences inequality within countries, the effect visualized in Fig. 2. This is represented by the "−2" summand in $\widetilde{\phi}$. Abatement leads to larger gains for high-income households in absolute terms as avoided damages are proportional to income. The high-income households however also pay larger abatement costs in absolute terms. If equality is preferred at the global level, both effects tend to increase the SCC in the country with the largest inequality because high-income households will pay most of the additional abatement costs. The SCC tends to decrease in countries with less inequality to avoid decreasing damages primarily for high-income households in the unequal countries.

Second, the social value of increasing consumption changes under inequality – the effect visualized in Fig. 1. This is represented by the "μ_{CC}" summand in $\widetilde{\phi}$. This second effect offsets the first one if $\mu_{CC} > 0$. In this case, increasing consumption of a low-income household leads to a disproportionately larger increase in utility compared to increasing consumption of high-income households. This effect tends to decrease the SCC in the country with the largest inequality to avoid abatement costs for low-income households and increases the SCC in more equal countries to avoid damages to low-income households in unequal countries.

Both effects are offset if preferences differ from equality at the global level. If high-income households receive a higher global weight ($\text{cov}(w,i) > 0$), it is socially valuable that they experience larger avoided damages in absolute terms and not socially valuable that they bear larger abatement costs. This third effect is represented by the "1" summand and offsets the first effect described in the two previous paragraphs. Additionally, the social value of avoided damages or lower abatement costs of low-income households is less (represented by the "$-\mu_C$" summand in $\widetilde{\phi}$), which offsets the second effect in the above paragraph. The opposite holds if low-income households receive a higher welfare weight ($\text{cov}(w,i) < 0$).

Lastly, consider the aggregation of non-market benefits in $\widetilde{\varphi}$. Inequality influences the social value of increasing abatement (the effect visualized in Fig. 1). If equality is preferred at the global level and marginal utility of abatement is concave (the term with $\lambda_C\lambda_{CC}$ in $\widetilde{\varphi}$ is negative), the presence of inequality tends to decrease the aggregate benefit of abatement and hence the SCC for all countries. If marginal utility of abatement is convex, the opposite holds. If inequality is preferred at the global level ($\text{cov}(w,i) > 0$), the SCC tends to increase for all countries if high-consumption households gain more from non-market benefits (the case of $\lambda_C < 0$) because these utility gains receive higher global weight.

Lemmas 1 and 2 show that the influence of inequality on the SCC is ambiguous. We next show that inequality tends to increase the SCC of all countries when damages disproportionately affect low-income households and are not compensated. This case is important, as empirical research shows that low-income households are more vulnerable to climate change (see Ahmed et al., 2009; Leichenko and Silva, 2014; Letta et al., 2018) and because national institutions may face capacity constraints when redistributing.

As we have seen so far, the effects of inequality can be countervailed through appropriate choices of the global welfare weights. To single out the influence of a higher burden on low-income households, we set the global weights at the household level to equality for the following lemma, i.e. $w_{t,k,j} = \overline{w}_{t,k}$. We also discuss the effect of global weights that diverge from equality.

Lemma 3. *Assume that abatement costs are proportional to income, global welfare weights are equal at the household level ($w_{t,k,j} = \overline{w}_{t,k}$) and damages fall disproportionately on low-income households ($\text{cov}_{t,k}(\delta,i) < 0$). If damages are small compared to total consumption,[12] the SCC tends to increase for each country compared to the case where damages are proportional to income. The SCC is approximated by*:

$$\tau_{t,p}|_{\text{NaSuOpB}} \approx \tau_{t,p}|_{\text{NaSuOpA}} + \underbrace{\frac{\sum_{T=t}^{t_{\text{end}}} \frac{1}{(1+\rho)^{T-t}} \sum_k H_{t,k}\overline{w}_{T,k}\text{muc}_{T,k}\overline{\text{d}}'_{T,k}(\mu_C)_{t,k}\frac{\text{cov}_{t,k}(\delta,i)}{\overline{i}_{t,k}}}{\overline{w}_{t,p}\text{muc}_{t,p}\left\{1+\widetilde{\phi}_{t,p}\right\}}}_{>0} \quad \forall\, p,t,$$

which is the sum of the SCC obtained when damages are proportional to income and a positive term capturing disproportionate damages to low-income households.

Proof. *We prove the Lemma by applying a second-order Taylor approximation in the variables $\delta_{t,k,j}$ and $i_{t,k,j}$ of* Eq. (13). *For details see App. A.7.* □

Lemma 3 shows a clear effect of inequality on the SCC. If damages accrue disproportionately to low-income households in

[11] One can show that the approximations in Eqs. (11) and (15) are the same when setting the welfare weights to $z_{t,k,j} = \frac{H_{t,k}}{\sum_s (i_{t,k,s})^{\eta}}(i_{t,k,j})^{\eta}$ and applying a second-order Taylor approximation of these weights around the income levels $i_{t,k,s}$.

[12] If damages are large, additional terms enter the approximation. See App. A.7 for details.

only one country, the SCC of all countries tends to increase compared to Lemma 2. A global increase in the SCC mitigates higher inequality by avoiding damages to low-income households. It can additionally be shown that the SCC increases globally, albeit to a lesser extent, as long as global preferences do not exactly align with existing inequality, i.e. global weights are different from Negishi weights.[13]

At the global level, the SCC increases because the national level fails to compensate low-income households for excessive climate damages. Therefore, the value of abatement critically increases under inequality.

4. Extensions

This section extends our analytical model in two respects. In Sec. 4.1, we check in how far our results are sensitive to assuming no international transfers. In Sec. 4.2, we use the numerical model NICE to derive quantitative SCC estimates under within-country inequality.

4.1. The role of international transfers

In this section, we relax the assumption that there are no international transfers. In the absence of international transfers, the SCC is generally differentiated by country, as optimal carbon prices need to account for income differences between countries (Chichilnisky and Heal, 1994). We proceed as follows: First, we analyze the case of unlimited lump-sum transfers between countries. We show that the SCC is uniform across countries if international transfers add to the national budget and redistribution is nationally optimal or if international transfers are used in proportion to the income of households and national transfers are suboptimal otherwise. In both cases, inequality within countries still in general influences the level of the unique SCC. Second, we discuss the more realistic case of restricted international transfers. For climate change, the international community has pledged to mobilize 100 bln USD per year for financing adaptation and mitigation in developing countries, with the Green Climate Fund as a main institution to distribute the resources. Climate finance under the UNFCCC has been criticized for being too low and for not reaching the funding goals (Yeo, 2019; Weikmans and Roberts, 2017). We discuss the role of restricted transfers within our model, and what they should ideally be targeted at.

Consider first the case of equality within countries and free redistribution at the global level. International transfers then simply change the mean consumption of the representative agent. To calculate the SCC, we adjust the maximization of Sec. 3.1 by inserting the composite consumption $\mathrm{c}_{t,k,j} - \mathrm{d}_{t,k,j} = \bar{\mathrm{i}}_{t,k} - \overline{\mathrm{m}}_{t,k} + \frac{\mathrm{L}_{t,k}}{\mathrm{H}_{t,k}} - \overline{\mathrm{d}}_{t,k}$ and adding the constraint that international transfers add up to zero $\sum_k \mathrm{L}_{t,k} = 0$.

With unlimited international transfers, the rule for the SCC remains the same as in Sec. 3.1, Eq. (5). We only get the additional condition that the marginal social value of consumption is equalized between countries:

$$\kappa_t = \overline{w}_{t,p} \mathrm{muc}_{t,p}, \quad \forall\, p, t$$

The SCC is the same in all countries because transfers freely distribute between countries, which can be easily seen by inserting the additional condition in the rule for the SCC. Because international transfers can be used to offset inequality between countries, country-specific are obsolete.

For inequality within countries and nationally optimal transfers, international transfers add to the general budget of each country. To calculate the SCC, we adjust the maximization of Sec. 3.2.1 by changing the budget to $\sum_j \ell_{t,k,j} = \tau_{t,k} \sum_j (e_{t,k,j} - \mathrm{a}_{t,k,j}(\tau_{t,k})) + \mathrm{L}_{t,k}$ and again adding the constraint that international transfers add up to zero $\sum_k \mathrm{L}_{t,k} = 0$.

As before, the rule for the SCC remains the same as in Sec. 3.2.1, Eq. (8). Unlimited international transfers now lead to equality of the weighted marginal social value of consumption:

$$\kappa_t = \frac{\sum_j \frac{w_{t,p,j} \mathrm{muc}_{t,p,j}}{z_{t,p,j} \mathrm{mucc}_{t,p,j}}}{\sum_j \frac{1}{z_{t,p,j} \mathrm{mucc}_{t,p,j}}}, \quad \forall\, p, t$$

Again, the SCC is the same in all countries, which can be easily seen by inserting the additional condition in the rule for the SCC. International transfers are used to offset inequality between countries, and country-specific SCC's become obsolete. Equal weighted marginal social values of consumption, κ_t, however take into account that international transfers cannot equalize

[13] The Proof is straightforward. If global welfare weights differ from $\overline{w}_{t,k}$, the approximation in Lemma 3 is adjusted by including the welfare weights in the second-order Taylor approximation:

$$\tau_{t,p}|_{\mathrm{NaSuOpB}} \approx \tau_{t,p}|_{\mathrm{NaSuOpA}} + \frac{\sum_{T=t}^{t_{\mathrm{end}}} \frac{1}{(1+\rho)^{T-t}} \sum_k H_{t,k} \overline{w}_{T,k} \mathrm{muc}_{T,k} \overline{\mathrm{d}}'_{T,k} \left[(\mu_C)_{t,k} \frac{\mathrm{cov}_{t,k}(\delta, i)}{\bar{\mathrm{i}}_{t,k}} - \frac{\mathrm{cov}_{t,k}(\delta, w)}{\overline{w}_{t,k}} \right]}{\overline{w}_{t,p} \mathrm{muc}_{t,p} \left\{ 1 + \widetilde{\phi}_{t,p} \right\}}.$$

Negishi weights are $w_{t,k,j} = B_t / \mathrm{muc}_{t,k,j}$ with a normalization parameter B_t (Chichilnisky and Heal, 1994; Nordhaus and Yang, 1996). Applying a second-order Taylor approximation of the weights w in income i and damage parameter δ yields $\mathrm{cov}_{t,k}(\delta, w) \approx \overline{w}_{t,k} (\mu_C)_{t,k} \mathrm{cov}_{t,k}(\delta, i)$, so that the additional summand is zero.

marginal social values of consumption between all households, as in the case of equality within countries. International transfers rather influence inequality within countries because a higher or lower national budget changes how the national level redistributes. The effect of international transfers on within-country inequality is anticipated at the global level and the SCC is adjusted accordingly.

For nationally suboptimal transfers, we have to determine how international transfers distribute within countries. As a plausible case, we assume that international transfers increase or decrease consumption of households in proportion to their income (for example through a change in the national flat income). Further, we assume that mitigation costs are proportional to income.

To calculate the SCC, we adjust the maximization of Sec. 3.2.2 by changing the constraints to $\mathrm{f}_{t,k,j} = \ell_{t,k,j} - \tau_{t,k} \cdot (e_{t,k,j} - \mathrm{a}_{t,k,j}) + \frac{i_{t,k,j}}{\bar{i}_{t,k}} \frac{\mathrm{L}_{t,k}}{H_{t,k}} = 0$ and adding the constraint that international transfers add up to zero $\sum_k \mathrm{L}_{t,k} = 0$. As before, the rule for the SCC remains the same as in Sec. 3.2.2, Eq. (13). International transfers again lead to equality of the following weighted marginal social value of consumption that is different from the case of nationally optimal transfers:

$$\kappa_t = \sum_j w_{t,p,j} \mathrm{muc}_{t,p,j} \frac{i_{t,p,j}}{H_{t,p} \bar{i}_{t,p}} = \sum_j w_{t,p,j} \mathrm{muc}_{t,p,j} \frac{\frac{\partial \mathrm{a}_{t,p,j}}{\partial \tau_{t,p}}}{\sum_s \frac{\partial \mathrm{a}_{t,p,s}}{\partial \tau_{t,p}}} \; \forall\, p, t$$

The last equality holds under the assumption that mitigation costs are proportional to income (see App. A.6). Again, the SCC is the same in all countries, which can be seen by inserting the additional condition in the rule for the SCC. As transfers preserve inequality within countries, the reason for a unique SCC is again that international transfers are used to offset inequality between countries. The level of the SCC is however still influenced by inequality: if damages fall disproportionately on the poor, a higher level for all countries is warranted to protect the poor as in Lemma 3.

In the following, we relax the assumption of unlimited international transfers. In the context of climate change, transfers are restricted and targeted at reducing mitigation costs and damages for low-income countries. A detailed account of the distributional impact of such transfers is beyond the scope of this paper. We therefore resort to discussing their impact qualitatively in the next two paragraphs, rather than doing a formal evaluation.

For the case of inequality and nationally suboptimal transfers (and trivially for equality within countries), only the total level of international transfers matters, while international transfers targeted at mitigation costs or damages do not change the final distribution of consumption within countries. (The national level distributes total available consumption according to its preferences, the initial distribution of available consumption does not play a role, see Sec. 3.2.1.) If transfers are restricted at the international level, they will be used in the direction of equalizing the (weighted sum of) marginal utility of consumption: countries with on average lower consumption and higher welfare weight tend to be recipients. As the level of transfers hit their constraint, country-specific SCC's will again be optimal in this constrained scenario. At the binding constraints, the conclusions of Sec. 3.2.1 remain valid.

For the case of nationally suboptimal transfers, it is again important how international transfers are used at the national level. If transfers reduce mitigation costs and damages proportional to income, their impact is equivalent to the one discussed above for distributing transfers in proportion to income. At the global level, transfers will again be used in the direction of equalizing the weighted sum of marginal utilities of consumption, with country-specific SCC's being optimal when the constraint is binding. Inequality again influences the level of the SCC as in Sec. 3.2.2. If international transfers are targeted at compensating disproportionate damages to the poor, they reduce the coefficient of correlation in Prop. 3. In this case, higher global SCCs are no longer required to shield poor households from damages. Such targeted international transfers reduce the need for a high mitigation effort at the global level.

4.2. Numerical simulations

This section uses the Nested Inequalities Climate Economy model (NICE) (Dennig et al., 2015; Budolfson et al., 2017) to quantitatively assess how the SCC changes under inequality. NICE is based on the Integrated Assessment Model RICE (Nordhaus, 2010), which disaggregates the global economy into twelve regions.[14] In NICE, each of these regions is further disaggregated into five income quintiles. The income of quintiles is a share of the regional total. The income shares are based on empirical estimates and can be found in Table SI 1 of Dennig et al. (2015). We denote the income share of quintile j in region k as $i\_share_{k,j}$. Income shares are constant over time and describe the baseline inequality of regions. Fig. A.6 in the Appendix shows regional Gini-coefficients. The figure also plots how, over time, inequality between the regions in NICE reduces because of regional convergence in total factor productivity. This study diverges from Dennig et al. (2015) by including national redistribution and allowing for regionally specific carbon taxes.

[14] While we largely avoid making model parameters explicit in the analytical part of the manuscript, we are relying on assumptions on parameter values and the functional form of the damage function in the current section. We are aware that such assumptions introduce a source of uncertainty into the model (Pindyck, 2017). However, using this approach allows us to compare our results to earlier literature using a similar approach, but not accounting for subregional heterogeneity. An alternative modeling approach would be to calibrate the model eliciting expert judgements, as for instance in Howard and Sylvan (2020) and (Hänsel et al., 2020).

The SCC is determined as the maximum of a global social welfare function when equality is preferred at the global level. It takes the constant elasticity form as in Eq. (4):

$$SWF = \sum_t \frac{1}{(1+\rho)^t} \sum_{t,k,j} pop_{t,k,j} \left[\left(\frac{c_{t,k,j} - d_{t,k,j}}{pop_{t,k,j}} \right)^{1-\eta} - 1 \right] / (1-\eta) \tag{17}$$

for $\eta \neq 1$ and log-utility otherwise. The population of quintile j in region k at time t is $pop_{t,k,j}$. Income net of mitigation costs determines quintile consumption $c_{t,k,j}$. In the basic NICE model the distribution of climate change damages $d_{t,k,j}$ and abatement costs over quintiles can be varied and enters as an assumption.

The pure time preference rate is 1.5%. A majority of experts considers this value too high (Drupp et al., 2018), but we deliberately choose it to demonstrate that even with such a high value, subnational inequality significantly increases the SCC. In two sensitivity runs, we check and confirm our results for $\rho = 1\%$ and $\rho = 2\%$, App. A.9.

We extend the NICE model by implementing the three cases of Sec. 3. To illustrate the quantitative impact of inequality and national redistribution, we treat the regions in NICE that aggregate multiple countries as one country for all three redistribution schemes.

The case of equality (Sec. 3.1**):** Each quintile gets the same share of regional composite consumption, which is equivalent to studies of the SCC with a representative agent (Nordhaus, 2017; Adler et al., 2017; Ricke et al., 2018).

Nationally optimal transfers (Sec. 3.2.1**):** We let each income quintile's share of regional composite consumption follow Eq. (10). The weights $z_{t,k,j}$ for each region k and quintile j are calculated in the following way: Given a regional consumption level, the national maximization leads to each quintile's share of consumption to be proportional to its income share $i\_share_{k,j}$. This amounts to assuming that the currently observed income distribution is considered optimal by each region and is preserved over the future.[15]

Nationally suboptimal transfers (Sec. 3.2.2**):** We use the same specification of quintile consumption as in Dennig et al. (2015). Pre-damage consumption of quintiles is proportional to the income share $i\_share_{k,j}$ of quintiles, which is equivalent to our formulation in Sec. 3.2.2. Each quintile receives a share of the regional climate damages, denoted $d\_share_{k,j}$. The shares can be varied from being proportional to being more or less than proportional to the income share, which is computed through the income elasticity of damage ξ: $d\_share_{k,j} \propto (i\_share_{k,j})^{\xi}$. If $\xi = 1$, damages are proportional to income shares and we have the same setting of NICE as in Lemma 2. If $\xi < 1$, damages fall disproportionately on low-income quintiles and we have the setting of Lemma 3.[16]

For the three cases, Fig. 3 shows the time-path of the SCC for the USA and Latin America until 2100. The SCC grows over time until it reaches the level of the backstop technology in the USA. Comparing the SCC paths shows that inequality between quintiles can have a large impact on the SCC when transfers are nationally suboptimal, which we now discuss in detail.

Consider first the case of equality within countries. In Fig. 3, the USA has a larger SCC than Latin America. This shows the quantitative impact of the effect discussed in Sec. 3.1: the SCC of the higher-income USA should be larger than of lower-income Latin America region as equality is preferred at the global level.

Concerning the impact of inequality under nationally optimal transfers, Fig. 3 shows that the SCC decreases moderately for the USA and increases moderately for Latin America. This effect is derived in Lemma 1: the SCC may increase or decrease for each region depending on the relative level of inequality and the consumption elasticity $\eta \lesseqgtr 1$. Nationally suboptimal transfers lead to increases in the SCC in both regions. We detail this case when discussing Fig. 5 below.

To further investigate the quantitative effects, Fig. 4 displays the relative change of the SCC under inequality compared to equality within countries. Transfers are nationally optimal. The regions which exhibit the highest (Africa), lowest (Japan) and an average (China) level of inequality in the NICE model are considered. Inequality is measured with the standard deviation in the income shares. On the horizontal axis, the elasticity of marginal felicity of the isolelastic utility function in Eq. (17) is varied. In line with Lemma 1, the country with the smallest inequality – Japan – has a larger SCC for $\eta > 1$ and a smaller SCC if $\eta < 1$ compared to equality. The reverse holds for Africa. For China, changes are more moderate but the figure shows that it tends toward the behavior of Japan. The SCC does not change from the equality case if utility is logarithmic. The numerical estimates with NICE show that the magnitude of change can become significant if η diverges from unity. The SCC increases or decreases by roughly 20% if η increases to 1.5 and by roughly 40% for $\eta = 2$ for the respective regions. Note that the backstop technology limits Japan's relative change when $\eta = 2$.

Lastly, we estimate the quantitative impact of nationally suboptimal transfers. Fig. 4 also displays the quantitative effects of Lemma 2 if damages are proportional to income (i.e. the income elasticity of damages is $\xi = 1$). In this case, composite consumption of quintiles is proportional to their income share so that the SCC differs from the case of equality in the same way under nationally optimal and suboptimal transfers (see discussion below Lemma 2).

Figs. 3 and 5 display a larger increase in the SCC across all regions when damages fall disproportionately on low-income quintiles and are not compensated – the numerical implementation of Lemma 3. The vertical axis of Fig. 5 shows the SCC for three countries (USA, India, China) under nationally suboptimal transfers. The figure compares the SCC to the equality case. If

[15] The Dennig et al. results on a globally uniform carbon tax carry over to our national redistribution schemes. The proportional damage case in Dennig et al. (2015) is the same as implementing the nationally optimal transfers defined here and nationally suboptimal transfers with proportional damages.

[16] With reference to Footnote 15, the results of Dennig et al. (2015) on a globally uniform tax with disproportionate damages to low-income quintiles carry over to this nationally suboptional transfer scheme.

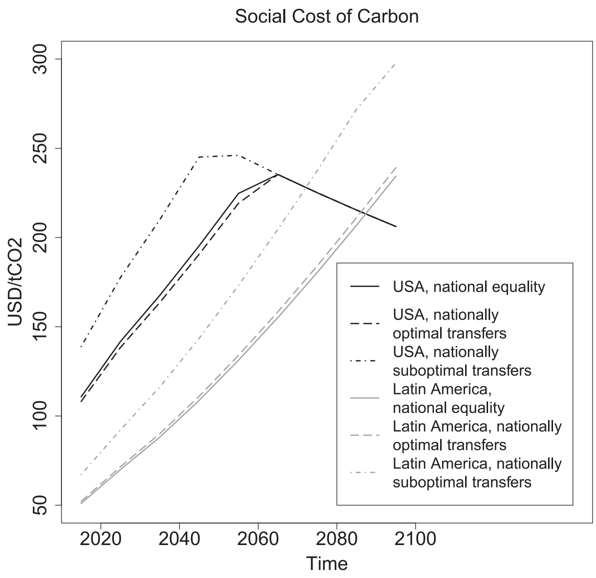

Fig. 3. The SCC over time for the USA and Latin America for the following cases: equality between quintiles in each country; inequality and nationally optimal transfers; inequality and nationally suboptimal transfers. The elasticity of marginal felicity is $\eta = 0.5$. The income elasticity of damages is $\xi = 0$, hence we are looking at the case in which damages fall disproportionately on low-income quintiles. We chose these two regions to illustrate our results, since they exhibit differences in income. In theory, any two regions with income differences would be suitable.

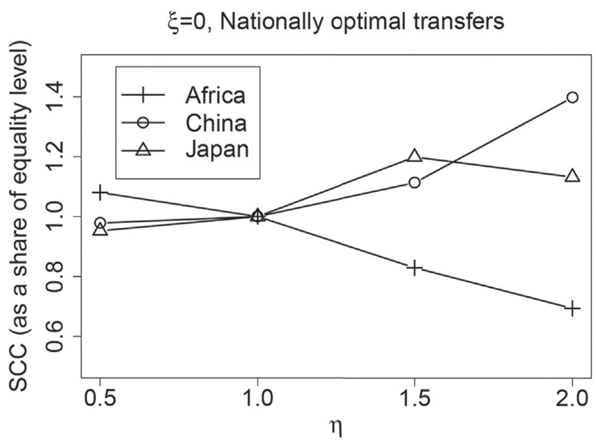

Fig. 4. The relative change of the SCC in the year 2035 compared to equality of quintiles within countries for different values of the elasticity of marginal felicity η and nationally optimal transfers. Displayed are NICE regions with the highest (Africa), lowest (Japan) and an average (China) level of inequality (measured with the standard deviation in the income shares).

damages are proportional to income ($\xi = 1$), the SCC diverges only moderately from the case of equality. When increasing damages to the low-income quintiles to the case, in which all quintiles experience the same absolute damage ($\xi = 0$), the SCC increases sharply compared to the equality case. For $\eta = 1.5$, the SCC more than doubles for India and China. The magnitude of change is especially pronounced, in line with Lemma 3, when η increases to 2, where the SCC is more than four times higher compared to equality. In the more extreme cases where the poor experience a larger absolute damage ($\xi < 0$), we even observe that the SCC is an order of magnitude larger in India and China for $\eta = 2$. The SCC of the USA reaches the value of the back-stop technology for $\eta = 1.5$ and does not change with introducing inequality within regions.

5. Conclusion

This article is the first to calculate the SCC with heterogeneity between and within countries, when the distribution within countries is endogenous. Traditionally, the SCC has been calculated in frameworks that model countries (or regions) as single representative agents. We identify the cases in which accounting for heterogeneity both between and within countries leads to large differences in the SCC compared to previous estimates.

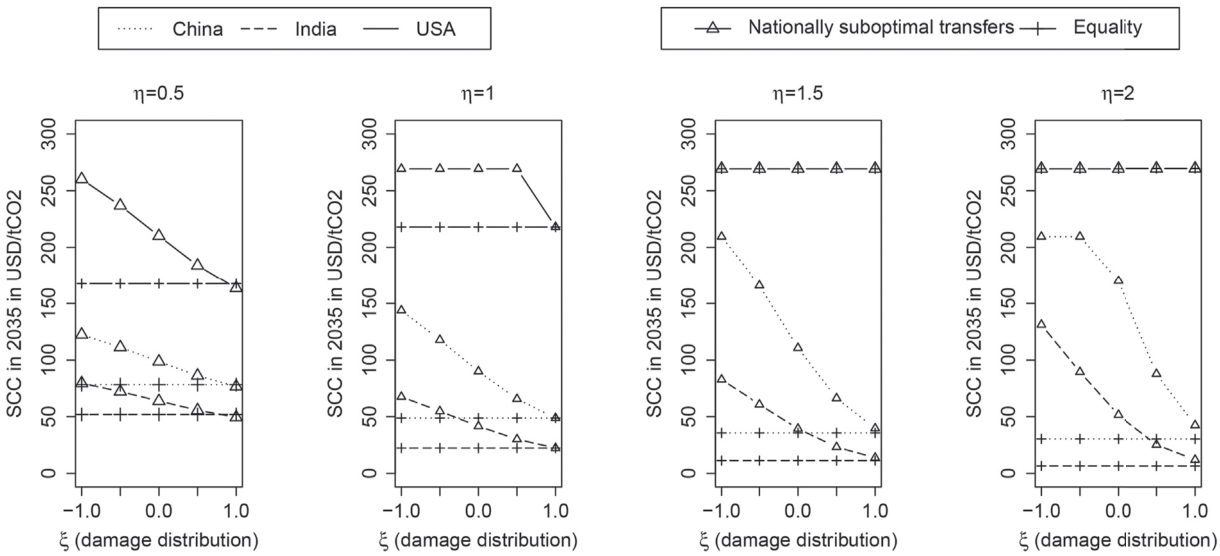

Fig. 5. The SCC in the year 2035 for different values of the elasticity of marginal felicity η, different damage distribution parameters ξ, nationally suboptimal transfers and the case of equality between quintiles. Climate damages to the lowest quintiles decrease from left to right.

Modeling heterogeneous households requires distinguishing between a global and a national level of governance. In our model, optimal climate policy is determined at the global level, while the national level redistributes between households within its jurisdiction. Carbon prices are assumed to be country-specific, which is likely more politically feasible and is also in line with the Common But Differentiated Responsibilities principle established in UN (1992). We characterize the SCC as a globally optimal set of national carbon taxes in this setting.

In this article, we show analytically that the SCC depends on the redistribution taking place within countries. We also compare the SCC when households are heterogeneous at the subnational level to the case of national representative agents (i.e. no heterogeneity within countries), which is the case that is most prominently discussed in the literature. We find that differences between the two cases are especially pronounced when climate damages fall disproportionately on lower-income households without compensation. Finally, we quantify these effects numerically for a standard range of parameter values.

These results have immediate relevance for policy makers, since the SCC is a benchmark measure for efficient carbon taxes. Climate and distributional policies can roughly be determined separately only if national institutions compensate households for excessive climate policy costs or climate damages and utility is approximately logarithmic. If the utility function deviates from the logarithmic form, changes in the SCC become larger. By contrast, if some national governments fail to compensate low-income households for substantial climate damages, for example due to a lack of institutional capacity, policy interactions are large, and the SCC in some countries can more than double. This can also be interpreted as a delicate balance between national insurance mechanisms against climate damages and globally ambitious mitigation efforts. If one is below optimal levels, the other becomes more important.

Globally, both climate change and the reduction of poverty and inequality are high on political agendas, but carbon pricing is often portrayed as being an additional burden on poor households. While a first-best solution to these problems would be a global uniform carbon price and unlimited financial transfers between countries (and between households within countries), this is clearly not feasible. In this paper, we analyze the more realistic scenario of regionally differentiated carbon taxes and no international transfers (Bauer et al., 2020). Our results demonstrate that higher carbon taxes may be called for on a global scale, particularly if some countries do not have the means to reimburse poor households for disproportionate climate damages. This does not mean, however, that carbon taxes should be used for redistribution beyond climate-related inequalities. In fact, in our main results, the optimal carbon tax equals zero if there are no climate damages.

One limitation of our framework is that governments rely on first-best lump-sum transfers for redistributing the carbon tax revenues. We choose this abstraction to highlight the importance of accounting for household heterogeneity when calculating the SCC in the simplest possible way. In the real world, national governments would be information-constrained, and interactions with the income tax system would have to be taken into account (Kaplow, 2012; Jacobs and de Mooij, 2015; Klenert et al., 2018). In addition, administrative costs of redistribution would have to be included. Such constraints would result in different degrees of leakiness in national and international redistribution, and an immediate interaction with optimal levels of carbon prices. Future research needs to take these real-world constraints into account and analyze further revenue recycling mechanisms currently discussed in the literature, such as tax cuts or uniform lump-sum recycling in a two-level governance framework.

Acknowledgements

The authors thank Francis Dennig and Maddalena Ferranna for helpful comments, suggestions and support with the NICE model. We also thank Christian Flachsland, Max Franks and Linus Mattauch for reviewing earlier versions of the paper and for valuable comments and suggestions. Lastly, we thank the participants of the conferences EAERE 2017 and LAGV 2018 as well as participants of seminars at the University of Princeton and UC Berkeley for valuable discussions.

Marc Fleurbaey worked on this manuscript while at the Woodrow Wilson School of Public and International Affairs-University Center for Human Values, Princeton University, Princeton, NJ 08544, USA, and received funding from Ciara Burnham. Ulrike Kornek worked on this manuscript while at the Princeton Environmental Institute, Princeton University.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ulrike Kornek received funding from the Deutsche Forschungsgemeinschaft (DFG) (Geschäftszeichen KO 5900/1-1).

A. Appendix

A.1. Solving the analytical model for general national redistribution

This section derives the SCC for general redistribution at the national level. To that end we analyze a general functional relationship that defines the level of transfers to each household through the constraint $\mathrm{f} = 0$. We let f be a function of the variables of our problem. The transfer to household j in country k is determined by $\mathrm{f}_{t,k,j} = \mathrm{f}_{t,k,j}(\ell_{t,k,1}, \dots, \ell_{t,k,H_{t,k}}, \mathrm{A}_t, \tau_{t,k}) = 0$. The determining variables are: (i) the transfer levels $\ell_{t,k,s}$ of all households of country k at time t, (ii) the stock of abatement A_t at time t, (iii) the tax level $\tau_{t,k}$ of country k.

The following optimization determines the SCC at the global level:

$$\max_{\tau_{t,k},\ell_{t,k,j}} \sum_{T=1}^{t_{\text{end}}} \frac{1}{(1+\rho)^T} \sum_{k,j} w_{T,k,j} \cdot \mathrm{u}(\mathrm{c}_{T,k,j} - \mathrm{d}_{T,k,j}(A_T), \mathrm{g}_{T,k}(\mathrm{A}_T)).$$

$$\text{s.t.} \qquad \sum_j [\ell_{t,k,j} - \tau_{t,k} \cdot (e_{t,k,j} - \mathrm{a}_{t,k,j})] = 0, \quad \forall k, t$$

$$\text{and} \qquad \mathrm{f}_{t,k,j}(\ell_{t,k,1}, \dots, \ell_{t,k,H_{t,k}}, \mathrm{A}_t, \tau_{t,k}) = 0, \quad \forall k, j, t.$$

Consumption is given by the budget constraint: $\mathrm{c}_{t,k,j} = i_{t,k,j} - \tau_{t,k} \cdot (e_{t,k,j} - \mathrm{a}_{t,k,j}(\tau_{t,k})) + \ell_{t,k,j} - \mathrm{m}_{t,k,j}(\mathrm{a}_{t,k,j}(\tau_{t,k}))$. Total abatement is $\mathrm{A}_t = \sum_{T=0}^{t} \sum_{k=1}^{N} \sum_{j=1}^{H_{T,k}} \mathrm{a}_{T,k,j}(\tau_{T,k})$ with $\mathrm{a}_{t,k,j}(\tau_{t,k})$ defined by Eq. (2).

The Lagrangian reads:

$$\mathcal{L} = \sum_T \frac{1}{(1+\rho)^T} \sum_{k,j} w_{T,k,j} \cdot \mathrm{u}(\mathrm{c}_{T,k,j} - \mathrm{d}_{T,k,j}(\mathrm{A}_T), \mathrm{g}_{T,k}(\mathrm{A}_T)) + \sum_T \sum_k \zeta_{T,k} \sum_j [\ell_{T,k,j} - \tau_{T,k} \cdot (e_{T,k,j} - \mathrm{a}_{T,k,j})] + \sum_T \sum_{k,j} \chi_{T,k,j} \mathrm{f}_{T,k,j}.$$

The government's first-order condition, rearranged to give the SCC, are:

$$\tau_{t,p} = \frac{1}{-\zeta_{t,p} \sum_s \frac{\partial \mathrm{a}_{t,p,s}}{\partial \tau_{t,p}}} \cdot \left(\sum_{T=t}^{t_{\text{end}}} \frac{1}{(1+\rho)^T} \sum_{k,j} w_{T,k,j} \left(\mathrm{muc}_{T,k,j} \cdot (-\mathrm{d}'_{T,k,j}) + \mathrm{mua}_{T,k,j} \right) \sum_s \frac{\partial \mathrm{a}_{t,p,s}}{\partial \tau_{t,p}} \right.$$

$$\left. + \sum_{T=t}^{t_{\text{end}}} \sum_{k,j} \chi_{T,k,j} \sum_s \frac{\partial \mathrm{f}_{k,j}}{\partial \mathrm{A}_T} \frac{\partial \mathrm{a}_{t,p,s}}{\partial \tau_{t,p}} + \sum_s \chi_{t,p,s} \left[\sum_j (e_{t,p,j} - \mathrm{a}_{t,p,j}) \frac{\partial \mathrm{f}_{t,p,s}}{\partial \ell_{t,p,j}} + \frac{\partial \mathrm{f}_{t,p,s}}{\partial \tau_{t,p}} \right] \right) \quad \forall\, p, t$$

$$\zeta_{t,p} = -\frac{1}{(1+\rho)^t} w_{t,p,j} \mathrm{muc}_{t,p,j} - \sum_s \chi_{t,p,s} \frac{\partial \mathrm{f}_{t,p,s}}{\partial \ell_{t,p,j}} \quad \forall\, j, p, t = \frac{1}{H_{t,p}} \sum_j \left(-\frac{1}{(1+\rho)^t} w_{t,p,j} \mathrm{muc}_{t,p,j} - \sum_s \chi_{t,p,s} \frac{\partial \mathrm{f}_{t,p,s}}{\partial \ell_{t,p,j}} \right) \quad \forall\, p, t$$

This expression for the SCC differs notably from the equality case in Eq. (5). There are two drivers of this difference:

1. Increasing consumption or abatement receives a different social value at the global level with inequality between households (see Fig. 1). Since marginal utilities of consumption and abatement are not equalized between households, the denominator and numerator in τ take account of these differences by taking an average across all households. Hence, when the marginal utilities are convex or concave functions, their sum will generally differ from their value at the mean.
2. The SCC changes inequality between households (see Fig. 2) with national distributional decisions anticipated at the global level. Different levels of the SCC influence the transfer to each household, reflected in the terms that include the Lagrange multipliers χ on the constraints f. The transfer generally changes with (i) the stock of abatement (derivative of f with respect to the stock of abatement) by changing avoided damages and non-market benefits of abatement; (ii) the SCC in a particular country (derivative of f with respect to the carbon tax rate), with different levels of total composite consumption in a country through different abatement costs and redistribution of the national tax revenue.

A.2. Approximation of the SCC around equality

In the rules for the SCC, the numerators and denominators generally depend on parameters $\vec{x}$, such as household income. Let equality of these parameters within countries be denoted by $\vec{\bar{x}}$. If n_x is the number of parameters, the second-order Taylor approximation of a function y (equal to the denominator or the numerator) is generally given by:

$$y(\vec{x}) \approx y(\vec{x} = \vec{\bar{x}}) + \sum_{n=1}^{n_x} \frac{\partial y}{\partial x_n}\Big|_{\vec{x}=\vec{\bar{x}}}(x_n - \bar{x}_n) + \frac{1}{2}\sum_{n1=1}^{n_x}\sum_{n2=1}^{n_x} \frac{\partial^2 y}{\partial x_{n1}\partial x_{n2}}\Big|_{\vec{x}=\vec{\bar{x}}}(x_{n1} - \bar{x}_{n1})(x_{n2} - \bar{x}_{n2}) \tag{A.1}$$

A.3. Derivation of SCC rule in Sec. 3.2.1

The constraints in Eq. (7) can be summarized by setting the weighted marginal utilities of consumption in each country k at time t to a variable $\epsilon_{t,k}$:

$$z_{t,k,j}\mathrm{muc}_{t,k,j} = \epsilon_{t,k} \quad \forall j$$

which governs how the national level redistributes total consumption $\sum_s c_{t,k,s} = \sum_s i_{t,k,s} - m_{t,k,s}(a_{t,k,s}(\tau_{t,k}))$ among households.

The maximization at the global level is (see also the online appendix that provides further detail):

$$\max_{c_{T,p,s},\tau_{T,p},\epsilon_{T,p}} \sum_{t=0}^{t_{\mathrm{end}}} \frac{1}{(1+\rho)^t}\sum_{k,j} w_{t,k,j}u(c_{t,k,j} - d_{t,k,j}, g_{t,k}(A_t))$$

$$\text{s.t.} \quad z_{t,k,j}\mathrm{muc}_{t,k,j} = \epsilon_{t,k} \quad \forall j,k,t$$

$$\sum_s c_{t,k,s} = \sum_s i_{t,k,s} - m_{t,k,s}(a_{t,k,s}(\tau_{t,k})) \quad \forall k,t.$$

The Lagrangian is

$$\mathcal{L} = \sum_{t=0}^{t_{\mathrm{end}}}\left(\frac{1}{(1+\rho)^t}\sum_{k,j}(w_{t,k,j}u(c_{t,k,j} - d_{t,k,j}(A_t), g_{t,k}(A_t)) + \chi_{t,k,j}(z_{t,k,j}\mathrm{muc}_{t,k,j} - \epsilon_{t,k})) + (\zeta_{t,k}(c_{t,k,j} + i_{t,k,j} - m_{t,k,j}))\right)$$

with $\chi_{t,k,j}$ and $\zeta_{t,k}$ the Lagrange-multipliers for the respective constraints. The two conditions for the optimum in Sec. 3.2.1 are obtained by rearranging the FOCs $\frac{\partial}{\partial c_{t,p,s}}\mathcal{L} = 0$, $\frac{\partial}{\partial \tau_{t,p}}\mathcal{L} = 0$, $\frac{\partial}{\partial \epsilon_{t,p}}\mathcal{L} = 0$ and setting $-(1+\rho)^t\zeta_{t,k} = \kappa_{t,k}$.

A.4. Derivation of Lemma 1

A.4.1. Showing Lemma 1(a)

Eq. (11) is derived by plugging in $\mu_C = \eta, \mu_{CC} = \eta + 1, \lambda_C = \lambda_{CC} = 0$ in Eq. (12). The statements are derived by comparing the $\phi_{t,k}$ for the different cases of η.

A.4.2. Showing Lemma 1(b)

Eq. (12) is derived by applying the second-order Taylor approximation given in Eq. (A.1) to the numerator and denominator in Eq. (8). The variables of approximation are $(w_{t,k,1}, \ldots, w_{t,k,H_{t,k}}, z_{tk,1}, \ldots, z_{t,k,H_{k,t}})\ \forall k,t$. The points of approximation are $\frac{1}{H_{t,k}}\sum_j w_{t,k,j} = \overline{w}_{t,k}$ and $z_{t,k,j} = 1$, which implies equality within countries. The numerator consists of separate summations over time steps and countries, which will now be approximated separately.

The following approximations are usually of functions of the general form $Y_{t,k} = \sum_j w_{t,k,j} \cdot y(z_{t,k,j}, \epsilon_{t,k}(\{z_{t,k,s}\}_{s=1..H_{t,k}})) \cdot n_{t,k}(\{z_{t,k,s}\}_{s=1..H_{t,k}})$. Here $\epsilon_{t,k}(\{z_{t,k,s}\}_{s=1..H_{t,k}})$ and$n_{t,k}(\{z_{t,k,s}\}_{s=1..H_{t,k}})$ are functions of the set of welfare weights, for which their value and values of the first and second derivatives with respect to the weights are equal at the mean of $z_{t,k,s}$ (see below). For such $Y_{t,k}$ the general approximation in (A.1) can be simplified:

$$
\begin{aligned}
\mathrm{Y}_{t,k} \approx & \mathrm{Y}_{t,k}|_{w=\overline{w}_{t,k},z=1} + \underbrace{\sum_{j=1}^{H_{t,k}} \frac{\partial \mathrm{Y}_{t,k}}{\partial w_{t,k,j}}|_{w=\overline{w}_{t,k},z=1}(w_{t,k,j}-\overline{w}_{t,k,j})}_{=0} + \underbrace{\sum_{s=1}^{H_{t,k}} \frac{\partial \mathrm{Y}_{t,k}}{\partial z_{t,k,s}}|_{w=\overline{w}_{t,k},z=1}(z_{t,k,s}-1)}_{=0} \\
& + \frac{1}{2}\sum_{j=1}^{H_{t,k}}\sum_{s=1}^{H_{t,k}} \underbrace{\frac{\partial^2 \mathrm{Y}_{t,k}}{\partial w_{t,k,j}\partial w_{t,k,s}}|_{w=\overline{w}_{t,k},z=1}}_{=0}(w_{t,k,j}-\overline{w}_{t,k})(w_{t,k,s}-\overline{w}_{t,k}) + \frac{1}{2}\sum_{j=1}^{H_{t,k}}\sum_{s=1}^{H_{t,k}} \frac{\partial^2 \mathrm{Y}_{t,k}}{\partial w_{t,k,j}\partial z_{t,k,s}}|_{w=\overline{w}_{t,k},z=1}(w_{t,k,j}-\overline{w}_{t,k})(z_{t,k,s}-1) \\
& + \frac{1}{2}\sum_{j=1}^{H_{t,k}}\sum_{s=1}^{H_{t,k}} \frac{\partial^2 \mathrm{Y}_{t,k}}{\partial z_{t,k,j}\partial w_{t,k,s}}|_{w=\overline{w}_{t,k},z=1}(z_{t,k,j}-1)(w_{t,k,s}-\overline{w}_{t,k}) + \frac{1}{2}\sum_{j=1}^{H_{t,k}}\sum_{s=1}^{H_{t,k}} \frac{\partial^2 \mathrm{Y}_{t,k}}{\partial z_{t,k,j}\partial z_{t,k,s}}|_{w=\overline{w}_{t,k},z=1}(z_{t,k,j}-1)(z_{t,k,s}-1)
\end{aligned}
$$

The first and second non-zero sums are the same and can be further manipulated:

$$
\begin{aligned}
& \sum_{j=1}^{H_{t,k}}\sum_{s=1}^{H_{t,k}} \frac{\partial^2 \mathrm{Y}_{t,k}}{\partial w_{t,k,j}\partial z_{t,k,s}}|_{w=\overline{w}_{t,k},z=1}(w_{t,k,j}-\overline{w}_{t,k})(z_{t,k,s}-1) \\
& = \sum_{j=1}^{H_{t,k}}\sum_{s=1,s\neq j}^{H_{t,k}} \ldots + \sum_{j=1}^{H_{t,k}} \frac{\partial^2 \mathrm{Y}_{t,k}}{\partial w_{t,k,j}\partial z_{t,k,j}}|_{w=\overline{w}_{t,k},z=1}(w_{t,k,j}-\overline{w}_{t,k})(z_{t,k,j}-1) \\
& = \underbrace{\frac{\partial^2 \mathrm{Y}_{t,k}}{\partial w_{t,k,j}\partial z_{t,k,s}}|_{w=\overline{w}_{t,k},z=1}}_{\text{for any } j\neq s} \left(\underbrace{\sum_{j=1}^{H_{t,k}}\sum_{s=1}^{H_{t,k}} (w_{t,k,j}-\overline{w}_{t,k})(z_{t,k,s}-1)}_{=0} - \sum_{j=1}^{H_{t,k}} (w_{t,k,j}-\overline{w}_{t,k})(z_{t,k,j}-1) \right) \\
& + \sum_{j=1}^{H_{t,k}} \frac{\partial^2 \mathrm{Y}_{t,k}}{\partial w_{t,k,j}\partial z_{t,k,j}}|_{w=\overline{w}_{t,k},z=1}(w_{t,k,j}-\overline{w}_{t,k})(z_{t,k,j}-1) \\
& = H_{t,k}\mathrm{cov}_{t,k}(w,z)\left(\frac{\partial^2 \mathrm{Y}_{t,k}}{\partial w_{t,k,j}\partial z_{t,k,j}} - \frac{\partial^2 \mathrm{Y}_{t,k}}{\partial w_{t,k,j}\partial z_{t,k,s}}|_{j\neq s} \right)|_{w=\overline{w}_{t,k},z=1}.
\end{aligned}
$$

The same type of manipulation for the remaining third non-zero summand above leads to the following formula:

$$
\begin{aligned}
\mathrm{Y}_{t,k} \approx & \mathrm{Y}_{t,k}|_{w=\overline{w}_{t,k},z=1} + H_{t,k}\mathrm{cov}_{t,k}(w,z)\left(\frac{\partial^2 \mathrm{Y}_{t,k}}{\partial w_{t,k,j}\partial z_{t,k,j}} - \frac{\partial^2 \mathrm{Y}_{t,k}}{\partial w_{t,k,j}\partial z_{t,k,s}}\Big|_{j\neq s} \right)\Bigg|_{w=\overline{w}_{t,k},z=1} \\
& + H_{t,k}\frac{1}{2}(\sigma^2_{t,k}(z))\left(\frac{\partial^2 \mathrm{Y}_{t,k}}{(\partial z_{t,k,j})^2} - \frac{\partial^2 \mathrm{Y}_{t,k}}{\partial z_{t,k,j}\partial z_{t,k,s}}\Big|_{j\neq s} \right)\Bigg|_{w=\overline{w}_{t,k},z=1}
\end{aligned}
\tag{A.2}
$$

The approximation in Eq. (12) is derived in deviations of $w_{t,k,j}$ and $z_{t,k,j}$ around their means $\overline{w}_{t,k}$ and 1. Inequality in income, benefits and costs of abatement between households is not taken into account because only the set of weights $\{z_{t,k,j}\}_{j=1..H_{t,k}}$ determines household inequality in composite consumption at the national level, which we show in detail in the following.

The composite consumption level of a household j in country k at time t is determined by the total level of composite consumption $\mathrm{C}_{t,k} - \mathrm{D}_{t,k} = \sum_j (\mathrm{c}_{t,k,j} - \mathrm{d}_{t,k,j})$ and its national welfare weight $z_{t,k,j}$ through Eq. (7):

$$
z_{t,k,j}\mathrm{muc}_{t,k,j} = z_{t,k,s}\mathrm{muc}_{t,k,s} = \epsilon_{t,k} \quad \forall j,s \tag{A.3}
$$

$$
\Rightarrow \mathrm{c}_{t,k,j} - \mathrm{d}_{t,k,j} = (\mathrm{muc}_{t,k})^{-1}\left(\frac{\epsilon_{t,k}}{z_{t,k,j}}\right) \tag{A.4}
$$

$$
\Rightarrow \mathrm{C}_{t,k} - \mathrm{D}_{t,k} = \sum_j (\mathrm{muc}_{t,k})^{-1}\left(\frac{\epsilon_{t,k}}{z_{t,k,j}}\right). \tag{A.5}
$$

Here $(\mathrm{muc}_{t,k})^{-1}$ is the inverse function of the marginal utility of consumption, which depends on the time and country index through the second argument of the utility function $\mathrm{u}(\mathrm{c}-\mathrm{d}, g(\mathrm{A}))$. Marginal utility of consumption has an inverse as it is a decreasing function. Eq. (A.4) defines household composite consumption based on the set of welfare weights $z_{t,k,s}, s \in \{1 \ldots H_{t,k}\}$.

Hence, we can express the value of equalized weighted marginal utilities of consumption, $\epsilon_{t,k}$, as a function of the weights $z_{t,k,j}$ that distribute $\mathrm{C}_{t,k} - \mathrm{D}_{t,k}$ in Eq. (A.5) around the national mean $\overline{\mathrm{c}}_{t,k} - \overline{\mathrm{d}}_{t,k}$ if all weights were equal $z_{t,k,j} = 1$. For the second-order approximation below, we will need the following expressions of $\epsilon_{t,k}$, which can be found by applying the implicit function theorem to Eq. (A.5):

$$\epsilon_{t,k}\Big|_{z_{t,k,j}=1} = \text{muc}_{t,k}$$

$$\frac{\partial \epsilon_{t,k}}{\partial z_{t,k,j}}\Big|_{z_{t,k,j}=1} = \frac{1}{H_{t,k}}\text{muc}_{t,k}$$

$$\left(\frac{\partial^2 \epsilon_{t,k}}{(\partial z_{t,k,j})^2} - \frac{\partial^2 \epsilon_{t,k}}{\partial z_{t,k,j}\partial z_{t,k,s}}\right)\Big|_{z_{t,k,j}=1} = -\frac{1}{H_{t,k}}\text{muc}_{t,k}\left\{\frac{[(\text{muc}_{t,k})^{-1}]''}{[(\text{muc}_{t,k})^{-1}]'}\text{muc}_{t,k} + 2\right\}. \tag{A.6}$$

Here, $[(\text{muc}_{t,k})^{-1}]'$ and $[(\text{muc}_{t,k})^{-1}]''$ are the first and second derivatives of the inverse function to the marginal utility of consumption, taken at mean consumption at household level in country k at time t. They can be calculated through the general law on derivatives of inverse functions as $[(\text{muc})^{-1}]' = \frac{1}{\text{mucc}}$ and $[(\text{muc})^{-1}]'' = -\frac{\frac{\partial \text{mucc}}{\partial c}}{(\text{mucc})^3}$. The general law on derivatives of inverse functions holds as muc is continuous and one-to-one, mucc < 0 and $\frac{\partial \text{mucc}}{\partial c}$ exists.

With (A.4) we can hence express the composite consumption level of each household as a function of national weights:

$$c_{t,k,j} - d_{t,k,j} = \text{muc}_{t,k}^{-1}\left(\frac{\epsilon_{t,k}(\{z_{t,k,s}\}_{s=1..H_{t,k}})}{z_{t,k,j}}\right)$$

With the last Eq. we can now approximate the denominator of (8)

$$\kappa_{t,k} = \frac{\sum_j \frac{w_{t,k,j}\text{muc}_{t,k,j}}{z_{t,k,j}\text{mucc}_{t,k,j}}}{\sum_j \frac{1}{z_{t,k,j}\text{mucc}_{t,k,j}}}$$

around $w_{t,k,j} = \overline{w}_{t,k}$ and $z_{t,k,j} = 1$. This is done by applying the approximation in (A.2). The differences in the derivatives are:[17]

$$\left(\frac{\partial^2 \kappa_{t,k}}{\partial w_{t,k,j}\partial z_{t,k,j}} - \frac{\partial^2 \kappa_{t,k}}{\partial w_{t,k,j}\partial z_{t,k,s}}|_{j\neq s}\right)|_{w_{t,k,j}=\overline{w}_{t,k}, z_{t,k,j}=1} = \frac{\text{muc}_{t,k}}{H_{t,k}}\left(\frac{(\mu_{CC})_{t,k}}{(\mu_C)_{t,k}} - 2\right)$$

and

$$\left(\frac{\partial^2 \kappa_{t,k}}{(\partial z_{t,k,j})^2} - \frac{\partial^2 \kappa_{t,k}}{\partial z_{t,k,j}\partial z_{t,k,s}}|_{j\neq s}\right)|_{w_{t,k,j}=\overline{w}_{t,k}, z_{t,k,j}=1} = -\frac{\overline{w}_{t,k}\text{muc}_{t,k}}{H_{t,k}}\left(\frac{(\mu_{CC})_{t,k}}{(\mu_C)_{t,k}} - 2\right)$$

Hence the approximation of the denominator, written down in Eq. (12), is:

$$\kappa_{t,p} \approx \overline{w}_{t,p}\text{muc}_{t,p}\left[1 + \left(\sigma^2_{t,p}(z) - 2\frac{\text{cov}_{t,p}(w,z)}{\overline{w}_{t,p}}\right)\left(1 - \frac{1}{2}\frac{(\mu_{CC})_{t,p}}{(\mu_C)_{t,p}}\right)\right] \tag{A.7}$$

The numerator can be split into three parts:

$$\sum_{T=t}^{t_{\text{end}}}\frac{1}{(1+\rho)^{T-t}}\left[\sum_k\left(\kappa_{T,k}H_{T,k}(-\overline{d}'_{T,k}) + \sum_j w_{T,k,j}\text{mua}_{T,k,j} - \sum_j\left(w_{T,k,j}\text{muc}_{T,k,j} - \kappa_{T,k}\right)\frac{\text{muac}_{T,k,j}}{\text{mucc}_{T,k,j}}\right)\right]$$

$$= \sum_{T=t}^{t_{\text{end}}}\frac{1}{(1+\rho)^{T-t}}\sum_k\left(V1_{T,k} + V2_{T,k} + V3_{T,k}\right)$$

The first part can be easily approximated with the approximation of $\kappa_{t,k}$ in (A.7):

$$V1_{t,k} = \kappa_{t,k}H_{t,k}(-\overline{d}'_{T,k}) \approx \overline{w}_{t,p}\text{muc}_{t,p}\left[1 + \left(\sigma^2_{t,p}(z) - 2\frac{\text{cov}_{t,p}(w,z)}{\overline{w}_{t,p}}\right)\left(1 - \frac{1}{2}\frac{(\mu_{CC})_{t,p}}{(\mu_C)_{t,p}}\right)\right]H_{t,k}(-\overline{d}'_{T,k})$$

[17] To derive these differences it is convenient to first represent the denominator generically because almost all first and second derivatives cancel:

$$\kappa_{t,k} = \frac{\sum_j \frac{w_{t,k,j}\text{muc}_{t,k,j}}{z_{t,k,j}\text{mucc}_{t,k,j}}}{\sum_j \frac{1}{z_{t,k,j}\text{mucc}_{t,k,j}}} = \sum_j w_{t,k,j}\cdot g(z_{t,k,j},\epsilon_{t,k})\cdot f(z_{t,k,j},\epsilon_{t,k})\cdot\left(\sum_s f(z_{t,k,s},\epsilon_{t,k})\right)^{-1}$$

with $g(z_{t,k,j},\epsilon_{t,k}) = \text{muc}_{t,k,j} = \frac{\epsilon_{t,k}}{z_{t,k,j}}$ and $f(z_{t,k,j},\epsilon_{t,k}) = \frac{1}{z_{t,k,j}\text{mucc}_{t,k,j}}$, where f is a function of consumption: $\text{mucc}_{t,k,j} = \text{mucc}(c_{t,k,j} - d_{t,k,j}) = \text{mucc}(\text{muc}^{-1}(\epsilon_{t,k}/z_{t,k,j}))$. Taking the derivatives of $\kappa_{t,k}$ then involves the derivatives of these functions with respect to $z_{t,k,j}$ and $z_{t,k,s}$, keeping in mind that ϵ is a function of these weights.

The second part can again be approximated with (A.2):

$$V2_{t,k} = \sum_j w_{t,k,j}\mathrm{mua}_{t,k,j} \approx H_{t,k}\overline{w}_{t,k}\mathrm{mua}_{t,k}\left(1 - \frac{\mathrm{cov}_{t,k}(w,z)}{\overline{w}_{t,k}}\frac{(\lambda_C)_{t,k}}{(\mu_C)_{t,k}} + \frac{1}{2}\sigma^2_{t,k}(z)\frac{(\lambda_C)_{t,k}(\lambda_{CC})_{t,k}}{{(\mu_C)_{t,k}}^2}\right)$$

The approximation of the third term can be obtained again by applying (A.2):[18]

$$V3_{t,k} = \kappa_{t,k}\sum_j \frac{\mathrm{muac}_{t,k,j}}{\mathrm{mucc}_{t,k,j}} - \sum_j w_{t,k,j}\mathrm{muc}_{t,k,j}\frac{\mathrm{muac}_{t,k,j}}{\mathrm{mucc}_{t,k,j}}$$

$$\approx H_{t,k}\overline{w}_{t,k}\mathrm{mua}_{t,k}\left[\frac{\mathrm{cov}_{t,k}(w,z)}{\overline{w}_{t,k}}\left(-\frac{(\lambda_C)_{t,k}}{(\mu_C)_{t,k}} + \frac{(\lambda_C)_{t,k}(\lambda_{CC})_{t,k}}{(\mu_C)^2_{t,k}}\right) - \sigma^2_{t,k}(z)\left(-\frac{(\lambda_C)_{t,k}}{(\mu_C)_{t,k}} + \frac{(\lambda_C)_{t,k}(\lambda_{CC})_{t,k}}{(\mu_C)^2_{t,k}}\right)\right]$$

Combining all three parts produces the numerator in Eq. (12).

A.5. *Detailed discussion of SCC rule in Eq. (12)*

First, consider how the marginal utility of consumption changes with inequality within countries, captured by ϕ. This factor appears in both the numerator and denominator because inequality changes the social value of increasing composite consumption in a country – either by decreasing damages (in the numerator) or decreasing costs in the country (in the denominator).

The effect of inequality within countries is best understood when we isolate it from the effects of global weights that diverge from equality. Setting global welfare weights to equality at the household level ($\mathrm{cov}(w,z) = 0$), we first consider the case of linear marginal utility of consumption when $\mu_{CC} = 0$. Because the marginal utility of consumption is neither convex nor concave, the social value of increasing consumption or abatement does not change under inequality (the effect of Fig. 1 is absent). The SCC will however still impact inequality at the household level (the effect of Fig. 2). If $\mu_{CC} = 0$, the national level will allocate over-proportionally more of a consumption increase to the households with the lowest national welfare weight.[19] With increasing total composite consumption that is available at the national level when the SCC increases from zero, inequality among households hence decreases. Indeed, Eq. (12) shows that the SCC tends to decrease for the country with the largest inequality and increase for the country with the lowest inequality. By assigning the different SCC, inequality in the most unequal country is reduced, which is beneficial if equality is preferred at the global level.

For $\mu_{CC} > 0$ the above identified effect is mitigated. In this case, the marginal utility of consumption of a low-consumption household, the one with a lower national weight, is disproportionately larger compared to households with higher consumption, the ones with larger weights. To achieve equalization of weighted marginal utilities of consumption, the national governance level has to allocate more consumption to households that have a higher weight and less to households with a lower weight compared to $\mu_{CC} = 0$ when total composite consumption increases at the national level. The larger allocation to higher-consumption households is not socially beneficial if equality is preferred at the global level. Therefore, with $\mu_{CC} > 0$ the effect of the previous paragraph is mitigated. For $\mu_{CC} < 0$ the same holds vice versa.

Additionally, with $\mu_{CC} > 0$, inequality at the household level changes the social value of increasing consumption (the effect of Fig. 1). Because marginal utility of consumption is convex, low-consumption household's marginal utility is disproportionately

[18] Here it is, like in footnote 17, convenient to first represent the summand generically through:

$$V3_{t,k} = \kappa_{t,k}\sum_j \frac{\mathrm{muac}_{t,k,j}}{\mathrm{mucc}_{t,k,j}} - \sum_j w_{t,k,j}\mathrm{muc}_{t,k,j}\frac{\mathrm{muac}_{t,k,j}}{\mathrm{mucc}_{t,k,j}}$$

$$= \frac{\sum_j \frac{w_{t,k,j}\mathrm{muc}_{t,k,j}}{z_{t,k,j}\mathrm{mucc}_{t,k,j}}}{\sum_j \frac{1}{z_{t,k,j}\mathrm{mucc}_{t,k,j}}}\sum_j \frac{\mathrm{muac}_{t,k,j}}{\mathrm{mucc}_{t,k,j}} - \sum_j w_{t,k,j}\mathrm{muc}_{t,k,j}\frac{\mathrm{muac}_{k,j}}{\mathrm{mucc}_{k,j}}$$

$$= \sum_j w_{t,k,j}\cdot \mathrm{g}(z_{t,k,j},\epsilon_{t,k})\cdot \mathrm{f}(z_{t,k,j},\epsilon_{t,k})\cdot\left(\sum_s \mathrm{f}(z_{t,k,s},\epsilon_{t,k})\right)^{-1}\cdot\sum_s \mathrm{h}(z_{t,k,s},\epsilon_{t,k})\cdot \mathrm{f}(z_{t,k,s},\epsilon_{t,k})$$

$$-\sum_j w_{t,k,j}\mathrm{g}(z_{t,k,j},\epsilon_{t,k})\cdot \mathrm{f}(z_{t,k,j},\epsilon_{t,k})\cdot \mathrm{h}(z_{t,k,j},\epsilon_{t,k})$$

with $\mathrm{g}(z_{t,k,j},\epsilon_{t,k}) = \mathrm{muc}_{t,k,j} = \frac{\epsilon_{t,k}}{z_{t,k,j}}$, $\mathrm{f}(z_{t,k,j},\epsilon_{t,k}) = \frac{1}{z_{t,k,j}\mathrm{mucc}_{t,k,j}}$ and $\mathrm{h}(z_{t,k,j},\epsilon_{t,k}) = z_{t,k,j}\mathrm{muac}_{t,k,j}$.

[19] For $\mu_{CC} = 0$, marginal utility of consumption is linear: $\mathrm{muc}_{t,k,j} = K_1 - K_2\cdot(\mathrm{c}_{t,k,j} - \mathrm{d}_{t,k,j})$. With the constraint that weighted marginal utilities of consumption are equalized in Eq. (7), we can derive the level of consumption of each household as a function of total national composite consumption $\mathrm{C}_{t,k} - \mathrm{D}_{t,k}$ and the national welfare weights:

$$\mathrm{c}_{t,k,j} - \mathrm{d}_{t,k,j} = \frac{1}{K_2}\left(K_1 - \frac{1}{z_{t,k,j}}\frac{H_{t,k}K_1 - K_2(\mathrm{C}_{t,k} - \mathrm{D}_{t,k})}{\sum_s \frac{1}{z_{t,k,s}}}\right)$$

Increasing composite consumption $\mathrm{C}_{t,k} - \mathrm{D}_{t,k}$ of the country, the national level allocates consumption to each household inversely proportional to its weight.

larger than of a high-consumption household. Hence, even if the national level only allocates a smaller share of additional national consumption to low-consumption households, its social value is higher at the global level. Again, for $\mu_{CC} < 0$ the same holds vice versa. Both effects for $\mu_{CC} \neq 0$ are combined in the rule for the SCC.

Turning to how inequality within countries changes the aggregation of non-market benefits, the term φ, consider again the case where (i) equality is preferred at the global level, $\text{cov}(w, z) \equiv 0$; (ii) the elasticity λ_{CC} is zero. Marginal utility of abatement is then linear in composite consumption. Hence, inequality in composite consumption does not change the social value of abatement in non-market benefits at the global level (the effect of Fig. 1 is absent). However, a different level of non-market benefits influences how the national level redistributes between households (the effect of Fig. 2). If the marginal utility of abatement increases with consumption ($\lambda_C < 0$), high-consumption households gain more from non-market benefits. As the national level puts a higher weight on these households, it has a further incentive to increase their consumption to increase their utility from non-market benefits. This would increase inequality within countries. To counteract this effect, the SCC of all countries decreases at the global level ($\varphi < 0$). The same holds vice versa for $\lambda_C > 0$.

For $\lambda_{CC} > 0$ the effect is again mitigated. With $\lambda_{CC} > 0$, marginal utility of abatement still increases in consumption but with decreasing returns. Hence the national level has a lower incentive to increase consumption of high-consumption households under $\lambda_C < 0$.

In addition the social value of increasing abatement changes with inequality (the effect of Fig. 1). Both effects for $\lambda_{CC} \neq 0$ are combined in the factor φ.

Lastly, all discussed effects are mitigated if preferences over inequality align at the global and national level. The covariance between national and global welfare weights is positive in this case, $\text{cov}(w, z) > 0$. The changes of the SCC under inequality within countries are mitigated because inequality between households is actually preferred at the global level.

A.6. Derivation of Lemma 2

We start from the rule for the SCC in Eq. (13). The summands of the numerator in Eq. (13) can be transformed to:

$$\sum_j w_{t,k,j}\left\{\text{muc}_{t,k,j}(-\text{d}'_{t,k,j}) + \text{mua}_{t,k,j}\right\} \overbrace{=}^{\delta_{t,k,j}=0} \sum_j w_{t,k,j}\left(\text{muc}_{t,k,j}\cdot(-\overline{\text{d}}'_{t,k})\frac{i_{t,k,j}}{\bar{i}_{t,k}} + \text{mua}_{t,k,j}\right).$$

The denominator is

$$\sum_j w_{t,p,j}\text{muc}_{t,p,j}\frac{\frac{\partial \text{a}_{t,p,j}}{\partial \tau_{t,p}}}{\sum_s \frac{\partial \text{a}_{t,p,s}}{\partial \tau_{t,p}}} \overbrace{=}^{\frac{\partial \text{a}_{t,p,j}}{\partial \tau_{t,p}} = \frac{1}{\tau_{t,p}}\frac{i_{t,p,j}}{\bar{i}_{t,p}}\frac{\partial \overline{\text{m}}_{t,p}}{\partial \tau_{t,p}}} \sum_j w_{t,p,j}\text{muc}_{t,p,j}\frac{i_{t,p,j}}{H_{t,p}\bar{i}_{t,p}},$$

which follows from differentiating abatement costs: $\frac{\partial}{\partial \tau_{t,p}} m_{t,p,j}(\text{a}_{t,p,j}) = \frac{\partial}{\partial \tau_{t,p}}\left(\frac{i_{t,k,j}}{\bar{i}_{t,k}}\overline{\text{m}}_{t,k}\right) \rightarrow \tau_{t,p}\cdot\frac{\partial \text{a}_{t,p,j}}{\partial \tau_{t,p}} = \frac{i_{t,p,j}}{\bar{i}_{t,p}}\frac{\partial \overline{\text{m}}_{t,p}}{\partial \tau_{t,p}}$. Both $\text{muc}_{t,k,j}$ and $\text{mua}_{t,k,j}$ are functions of income through consumption: $\text{c}_{t,k,j} - \text{d}_{t,k,j}(\text{A}_t) = i_{t,k,j} - \frac{i_{t,k,j}}{\bar{i}_{t,k}}\overline{\text{m}}_{t,k}(\tau_{t,k}) - \frac{i_{t,k,j}}{\bar{i}_{t,k}}\overline{\text{d}}_{t,k}(\text{A}_t)$.

A.6.1. Showing Lemma 2(a)

Eq. (15) is derived by plugging in $\mu_C = \eta, \mu_{CC} = \eta + 1, \lambda_C = \lambda_{CC} = 0$ in Eq. (16). The statements follow from comparing $\widetilde{\Phi}_{t,k}$ for the different values for η.

A.6.2. Showing Lemma 2(b)

Eq. (16) is derived by applying a second-order Taylor approximation in the parameters $(w_{t,k,1}, \ldots, w_{t,k,H_{t,k}}, i_{t,k,1}, \ldots, i_{t,k,H_{t,k}})\ \forall k, t$ to the numerator and denominator above. The second-order approximation is a straightforward application of the rule in Eq. A.1. The points of approximation are $\frac{1}{H_{t,k}}\sum_j w_{t,k,j} = \overline{w}_{t,k}$ and $\frac{1}{H_{t,k}}\sum_j i_{t,k,j} = \bar{i}_{t,k}$, which imply household equality at the national level.

A.7. Derivation of Lemma 3

The lemma is obtained by applying formula (A.1) to the numerator and denominator in (13). The numerator consists of separate summations over the households of each country, which can be approximated separately:

$$\sum_j w_{t,k,j}\left\{\text{muc}_{t,k,j}(-\text{d}'_{t,k,j}) + \text{mua}_{t,k,j}\right\} = \overline{w}_{t,k}\sum_j\left(\text{muc}_{t,k,j}\left(\frac{i_{t,k,j}}{\bar{i}_{t,k}} + \delta_{t,k,j}\right)(-\overline{\text{d}}'_{t,k}) + \text{mua}_{t,k,j}\right).$$

The numerator is (see above)

$$\sum_j w_{t,p,j}\mathrm{muc}_{t,p,j}\frac{\frac{\partial \mathrm{a}_{t,p,j}}{\partial \tau_{t,p}}}{\sum_s \frac{\partial \mathrm{a}_{t,p,s}}{\partial \tau_{t,p}}} = \overline{w}_{t,p}\sum_j \mathrm{muc}_{t,p,j}\frac{i_{t,p,j}}{H_{t,p}\bar{i}_{t,p}}.$$

Both $\mathrm{muc}_{t,k,j}$ and $\mathrm{mua}_{t,k,j}$ are functions of income and the parameter δ through composite consumption: $\mathrm{c}_{t,k,j} - \mathrm{d}_{t,k,j} = i_{t,k,j} - \frac{i_{t,k,j}}{\bar{i}_{t,k}}\overline{\mathrm{m}}_{t,k}(\tau_{t,k}) - \left(\frac{i_{t,k,j}}{\bar{i}_{t,k}} + \delta_{t,k,j}\right)\overline{\mathrm{d}}_{t,k}(\mathrm{A}_t)$. The variables for the approximation are $\delta_{t,k,j}$ and $i_{t,k,j}$. The respective points of approximation are 0 and $\frac{1}{H_{t,k}}\sum_j i_{t,k,j} = \bar{i}_{t,k}$, which would lead to equality within countries.

The approximation is

$$\tau_{t,p}\Big|_{\mathrm{T}_{2b}} \approx \frac{1}{\overline{w}_{t,p}\mathrm{muc}_{t,p}\left\{1+\widehat{\varphi}_{t,p}\right\}}\sum_{T=t}^{t_{\mathrm{end}}}\frac{1}{(1+\rho)^{T-t}}\sum_k H_{t,k}\overline{w}_{T,k}\Bigg[\mathrm{muc}_{T,k}(-\overline{\mathrm{d}}'_{T,k})\Bigg\{1 - (\mu_C)_{t,k}\left(\frac{\mathrm{cov}_{t,k}(\delta,i)}{\bar{i}_{t,k}} - \frac{\overline{\mathrm{d}}_{t,k}}{\overline{\mathrm{c}}_{t,k}-\overline{\mathrm{d}}_{t,k}}\sigma^2_{t,k}(\delta)\right) + \widehat{\varphi}_{T,k}\Bigg\} + \mathrm{mua}_{T,k,j}\left\{1+\widehat{\phi}_{T,k}\right\}\Bigg].$$

with

$$\widehat{\varphi}_{t,k} = \underbrace{\left((\mu_{CC})_{t,k}-2\right)(\mu_C)_{t,k}\frac{1}{2}\frac{\sigma^2_{t,k}(i)}{(\bar{i}_{t,k})^2}}_{=\widetilde{\varphi}|_{\mathrm{cov}(w,i)\equiv 0}} - (\mu_C)_{t,k}\frac{\overline{\mathrm{d}}_{t,k}}{\overline{\mathrm{c}}_{t,k}-\overline{\mathrm{d}}_{t,k}}\left[\underbrace{\left((\mu_{CC})_{t,k}-1\right)\frac{\mathrm{cov}_{t,k}(\delta,i)}{\bar{i}_{t,k}}}_{I} - (\mu_{CC})_{t,k}\frac{\overline{\mathrm{d}}_{t,k}}{\overline{\mathrm{c}}_{t,k}-\overline{\mathrm{d}}_{t,k}}\frac{1}{2}\sigma^2_{t,k}(\delta)\right]$$

$$\widehat{\phi}_{t,k} = \underbrace{(\lambda_C)_{t,k}(\lambda_{CC})_{t,k}\frac{1}{2}\frac{\sigma^2_{t,k}(i)}{(\bar{i}_{t,k})^2}}_{=\widetilde{\phi}|_{cov(w,i)\equiv 0}} - (\lambda_C)_{t,k}\lambda_{CC}\big)_{t,k}\frac{\overline{\mathrm{d}}_{t,k}}{\overline{\mathrm{c}}_{t,k}-\overline{\mathrm{d}}_{t,k}}\left[\frac{\mathrm{cov}_{t,k}(\delta,i)}{\bar{i}_{t,k}} - \frac{1}{2}\sigma^2_{t,k}(\delta)\frac{\overline{\mathrm{d}}_{t,k}}{\overline{\mathrm{c}}_{t,k}-\overline{\mathrm{d}}_{t,k}}\right]$$

Neglecting all terms with $\frac{\overline{\mathrm{d}}_{t,k}}{\overline{\mathrm{c}}_{t,k}-\overline{\mathrm{d}}_{t,k}}$ as they are small by assumption of the proposition, we arrive at the approximation.

If damages become large compared to consumption, we cannot neglect the terms with $\frac{\overline{\mathrm{d}}_{t,k}}{\overline{\mathrm{c}}_{t,k}-\overline{\mathrm{d}}_{t,k}}$. Then, there are correction factors both in the numerator and the denominator. For the numerator, there is the term “I” in the factor $\widehat{\phi}$ above that can offset the effect described in the proposition if μ_{CC} is small. To see this, set it to zero $\mu_{CC} = 0$. To focus on the effect described in the proposition, set $\lambda_{CC} = 0$ also. We get the following approximation:

$$\tau_{t,p}|_{\mathrm{T}_{2b}} \approx \frac{1}{\overline{w}_{t,p}\mathrm{muc}_{t,p}\left\{1+\widehat{\phi}_{t,p}\right\}}\sum_{T=t}^{t_{\mathrm{end}}}\frac{1}{(1+\rho)^{T-t}}\sum_k H_{t,k}\overline{w}_{T,k}\Bigg[\mathrm{muc}_{T,k}(-\overline{\mathrm{d}}'_{T,k})\Bigg\{1+\widetilde{\phi}_{t,k} - (\mu_C)_{t,k}\left(\frac{\mathrm{cov}_{t,k}(\delta,i)}{\bar{i}_{t,k}} - \frac{\overline{\mathrm{d}}_{t,k}}{\overline{\mathrm{c}}_{t,k}-\overline{\mathrm{d}}_{t,k}}\sigma^2_{t,k}(\delta)\right) + (\mu_C)_{t,k}\frac{\overline{\mathrm{d}}_{t,k}}{\overline{\mathrm{c}}_{t,k}+\overline{\mathrm{d}}_{t,k}}\frac{\mathrm{cov}_{t,k}(\delta,i)}{\bar{i}_{t,k}}\Bigg\}\Bigg].$$

The last summand is negative for $\mathrm{cov}(\delta,i) < 0$. If $\frac{\overline{\mathrm{d}}_{t,k}}{\overline{\mathrm{c}}_{t,k}-\overline{\mathrm{d}}_{t,k}} > 1$, the last summand may offset the two previous positive ones, and thereby reverse the effect described in the lemma.

In the denominator, the term “I” constitutes a negative contribution to correction for income inequality if $\mu_{CC} = 0$. This again changes whether the SCC increases or decreases with inequality compared to Lemma 2.

With $\mu_{CC} \neq 0$ more terms enter the approximation and the dependence of the SCC on subnational equality becomes more complex.

A.8. Gini-coefficients in NICE

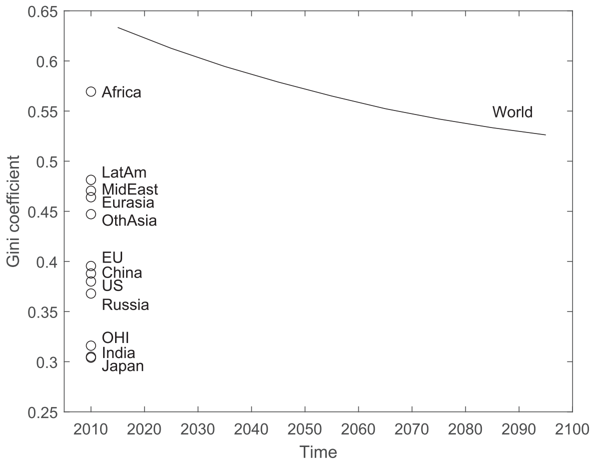

Fig. 6 Gini-coefficients for regions in the NICE model, which are constant over time, and global Gini-coefficient over time for nationally suboptimal transfers, $\xi = 1$ and $\eta = 1$.

A.9. Varying the rate of pure time preference in NICE

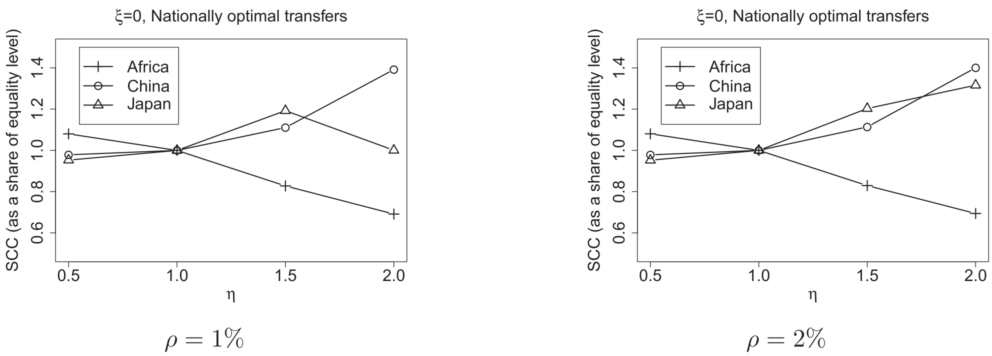

Fig. 7 Same setting as in Fig. 4 but with rate of pure time preference of $\rho = 1\%$ (left) and $\rho = 2\%$ (right).

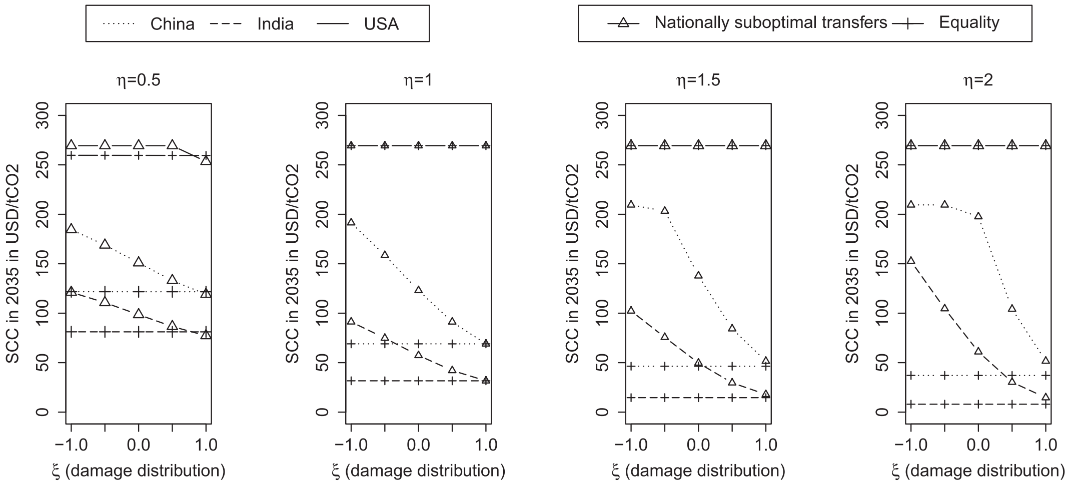

Fig. 8 Same setting as in Fig. 5 but with rate of pure time preference of $\rho = 1\%$.

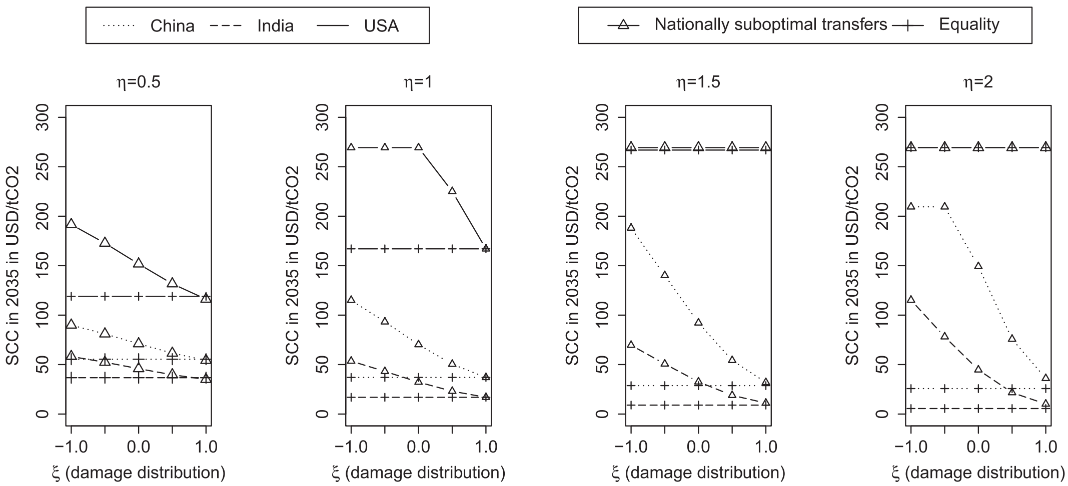

Fig. 9 Same setting as in Fig. 5 but with rate of pure time preference of $\rho = 2\%$.

A.10. List of symbols

t_{end}	number of periods
ρ	rate of pure time preference
t, T	time, runs from $1..t_{\text{end}}$
N	number of countries
k, p	country indices, run from $1..N$
$H_{t,k}$	number of households in country k at time t
j, s	household indices, run from $1..H_{t,k}$
u	utility function of households
$c_{t,k,j}$	consumption of household j in country k at time t
A_t	stock of abatement at time t
$g_{t,k}$	converts stock of abatement at time t to local climate in country k
$d_{t,k,j}(A_t)$	monetary damages as a function of abatement of household j in country k at time t
$muc_{t,k,j}$	marginal utility of consumption at composite consumption level $c_{t,k,j} - d_{t,k,j}$ and abatement level A_t
$mucc_{t,k,j}$	second derivative of utility with respect to consumption at composite consumption level $c_{t,k,j} - d_{t,k,j}$ and abatement level A_t
$mua_{t,k,j}$	marginal utility of abatement in non-market benefits at composite consumption level $c_{t,k,j} - d_{t,k,j}$ and abatement level A_t
$muac_{t,k,j}$	derivative of marginal utility of abatement with respect to consumption at composite consumption level $c_{t,k,j} - d_{t,k,j}$ and abatement level A_t
$\tau_{t,k}$	Social cost of carbon of country k at time t
$a_{t,k,j}$	abatement of household j in country k at time t
$e_{t,k,j}$	emissions of household j in country k at time t
$m_{t,k,j}(a_{t,k,j})$	abatement costs of household j in country k at time t
$i_{t,k,j}$	income of household j in country k at time t
$\ell_{t,k,j}$	transfer to household j in country k at time t
$w_{t,k,j}$	global welfare weight of household j in country k at time t
$\overline{(.)}_{t,k}$	mean of characteristic over households in country k at time t
$C_{t,k}, D_{t,k}$	aggregate consumption and damages in country k at time t
$(\cdot)'$	derivative of damage functions $(d, \overline{d})$ with respect to stock of abatement
$f_{t,k,j}$	constraint defining national transfer to household j in country k at time t
SWF, NWF	welfare function at global and national level, respectively
$\vec{x}\ x_n$	arrays of values and their components, respectively
η	elasticity of marginal felicity in the isoelastic utility function
$(\mu_C)_{t,k}, (\mu_{CC})_{t,k}, (\lambda_C)_{t,k}, (\lambda_{CC})_{t,k}$	elasticities at average composite consumption level of households in country k at time t
$\mathcal{L}, \zeta_{t,p}, \chi_{t,k,j}$	Lagrange function and multipliers
$\kappa_{t,k}$	transformation of Lagrange multiplier $\kappa_{t,k} = -(1+\rho)^t \zeta_{t,k}$
$\phi_{t,k}, \varphi_{t,k}, \widetilde{\phi}_{t,k}, \widetilde{\varphi}_{t,k}$	adjustment factors to the SCC from the equality case
$\sigma^2_{t,k}(\cdot)$	standard deviation of specific variable over all households in country k at time t
$cov_{t,k}(\cdot,\cdot)$	covariance of two specific variables over all households in country k at time t
$z_{t,k,j}$	national welfare weights
$\delta_{t,k,j}$	parameter defining how damages deviate from being proportional to income for household j in country k at time t
$\epsilon_{t,k}$	weighted marginal utility of consumption for nationally optimal transfers in country k at time t
$V1..3_{t,k}$	summands in the aggregated benefits from abatement under nationally optimal transfers
$pop_{t,k,j}, i\_share_{k,j}, d\_share_{k,j}$	population, income and damage shares of the NICE model of quintile j in region k at time t, respectively
ξ	income elasticity of damages in the NICE model

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jeem.2021.102450. The software of the NICE model is available for replication at https://github.com/Environment-Research/NICE-KornekETAL-JEEM-for-replication.

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