Who should abate carbon emissions? Optimal climate policy when national preferences determine its implementation

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Abstract

This article studies the effect of a previously neglected information asymmetry on the social cost of carbon (SCC). When the SCC is determined, a common assumption is that of a global social planner internalizing the climate damages. Countries are usually modeled as a representative agent. We argue that the common approach neglects a central determinant of the SCC: national governments that redistribute between heterogeneous households. We account for this additional level of governance. This leads to an information asymmetry between the global social planner and the national government concerning the redistribution between heterogeneous households. We show analytically that the SCC depends on national redistribution. Furthermore, we use numerical methods to estimate the scope of these effects over a range of utility functions and parameter values.

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1 Introduction

The social cost of carbon (SCC) have been a central measure for efficient climate policy, as recently highlighted by US Interagency Group (2015) deriving a range of SCC estimates to be employed in all US government agency regulatory impact assessments (Greenstone et al., 2013). A global social welfare function values costs of mitigation against damages, requiring normative assumptions on inequality aversion between the richest and poorest households. However, estimates of the SCC frequently rely on regional or country averages through a representative agent which may substantially decrease estimates of the SCC (Dennig et al., 2015). Assuming a representative agent seems to only be justified if a country authority were to implement optimal redistribution between households according to the global social welfare function. National redistribution is however a pre-requisite of the national government, whose preferences may differ from the global perspective. Our paper examines how distributional decisions at the national level influence the SCC.

A popular concept dealing with heterogeneity among households or countries to determine the SCC is applying equity weights. To internalize the climate externality, global marginal utilities of abatement are weighted by the marginal utility of consumption in this country, see (Anthoff et al., 2009; Azar and Sterner, 1996; Azar, 1999). However, these articles usually assume exogenous transfer schemes within countries, that critically influence marginal utilities of consumption and hence the SCC. Our article, by contrast, determines the SCC when countries differ in their income level and in the extent of redistribution that occurs within the country, determined by national preferences. We compare the implications of different preferences for redistribution on the national level to optimal redistribution, while excluding the possibility of transfers between countries.

Our main findings are as follows: first, we show analytically that the SCC of all countries can crucially depend on the redistribution that occurs within every other country. Especially when national governments reimburse households only with their tax payments without further transfers, household heterogeneity in damages can lead to a large deviation of the SCC as compared to the representative agent case. On the other hand, if national redistribution is based on a national social welfare function, we find that the SCC estimate is likely to differ only moderately if inequality and concavity of utility is moderate, even if transfers are far from optimal. Second, we use numerical methods to estimate the size of these effects over a wide range of utility functions and parameters. These findings add important insights to earlier literature on the social costs of carbon.

We draw on two important strands concerning the literature on optimal taxation (for a thorough understanding of the main issues involved in deriving the SCC, see Sterner and Kyriakopoulou (2012); Engström and Gars

(2015); Foley et al. (2013). First, the implications of optimal taxation in the presence of income inequality across countries have been first introduced by Chichilnisky and Heal (1994). They show that in general marginal abatement costs are equalized in the social optimum only if unrestricted lump-sum transfers between countries are allowed. Anthoff et al. (2009) restrict transfers between countries to zero and show the influence of equity weighting on the SCC of different world regions, for which households are aggregated to one representative agent. Dennig et al. (2015) introduce a more fine-grained sub-regional income distribution and show the effect on the SCC, which they constrain to be equal across agents. They only consider exogenous redistribution schemes between agents. Second, we draw on the literature that analyzes optimal taxation under informational constraints. This literature started with Mirrlees (1971) who determines optimal nonlinear income taxes in a model in which the government has no information about the households skill level and has to tax them according to their income without destroying their incentives to provide labor. In contrast to this literature our model has an additional level of governance – the social planner – and the constraint does not apply to the information national governments have about individual households, but to the information the social planner has about households within countries.

We extend the fundamental model of Chichilnisky and Heal (1994) to allow for two levels of regulatory decisions and heterogeneity in households at the national level. There is an information asymmetry between the global social planner and the national governments: the social planner is able to observe the distribution of climate damages, of the costs of mitigation, and of income on the country but not on the household level and thus needs to leave redistribution to the national regulator. The global social planner in our model provides a socially optimal benchmark. It cannot be interpreted as a federal government as in Roolfs et al. (2017) and hence the possibility of transfers between countries is excluded. When determining the SCC, the social planner anticipates different preferences for redistribution on the national level (as observable on an aggregate level via different Gini coefficients among countries).

Calculation of the SCC when national preferences take a generic form shows that there are several additional effects that determine second-best SCC. First, additional to the internalization of damages across all countries, the social planner anticipates a possible influence of abatement on national redistribution in every country, which changes the sum of the marginal utilities of abatement. Second, since weighted marginal utilities of consumption are possibly not equalized across households, weighted marginal utilities of consumption are averaged under anticipation of redistribution to convert marginal utilities of abatement to the SCC.

We consider two specific redistribution schemes: (i) households are reimbursed for their tax payments without further transfer (a common assumption in the literature on the SCC), (ii) the national government redistributes according to a national welfare function, which is a weighted sum of household utilities. For the first scheme we find that if market damages are homogeneous across households, second-best SCCs differ from optimal ones due to heterogeneity in income. If concavity of the utility function is low, differences are likely moderate. However, if damages fall disproportionally on poor households, the SCC of all countries can change to a large extend. The second redistribution scheme shows a different behavior. We find that for the case of an isoelastic utility function and market damages, differences in second-best taxes are moderate if concavity of the utility function is low. Interestingly, second-best taxes are equal to optimal ones for a logarithmic utility function. In this case, the difference of optimal transfers to second-best transfers may be arbitrarily large, but SCC estimates are unaffected, justifying the assumption of a representative agent.

In the second part of this article we use numerical experiments to quantify the influence of suboptimal redistribution on the SCC. We show that the magnitude of change depends on the form of the utility function, its parameter values, and the difference in preferences on the global and national level. Not as a surprise, changes increase as the difference in preferences grows. Changes are small for a constant elasticity of marginal felicity utility function when redistribution is based on a national welfare function. The SCC however changes to a large extend when transfers only reimburse tax payments and damages fall disproportionally on poor households.

The article is structured as follows: we describe the model in detail Section 2. In Section 3 we derive the main results analytically. Section 4 uses numerical methods to extend the analytical results and Section 5 concludes.

2 The model

Households: In each country i there are j households. Households derive their utility $u(c_{i,j}, a)$ from consumption $c_{i,j}$ and from cumulative abatement a. Their budget constraint is given by:

$$c_{i,j} + \tau_i(e_{i,j} - a_{i,j}) + \phi_{i,j}(a_{i,j}(\tau_i)) = I_{i,j} + L_{i,j}, \tag{1}$$

where τ_i denotes the emissions tax in country i, $I_{i,j}$ is the income of household j in country i, $e_{i,j}$ are the emissions and $a_{i,j}$ the abatement of that household, $\phi_{i,j}$ is the corresponding cost function of abatement, $L_{i,j}$ is the transfer that household j receives back from pollution tax revenue of country i. The total level of abatement a is given by the sum of the individual abatement efforts, so $a = \sum_{i,j} a_{i,j}$. Abatement is performed cost-efficiently, hence

$$\frac{\partial \phi_{i,j}}{\partial a_{i,j}} = \tau_i, \quad \forall j. \tag{2}$$

National Government: The national government in country i redistributes the revenues from the carbon tax τ_i by adjusting the transfer level $L_{i,j}$ each household receives. The sum of transfers in each country has to equal the tax revenue $\sum_j L_{i,j} = \tau_i \cdot \sum_j (e_{i,j} - a_{i,j})$, $\forall i$.

We first analyze a general functional relationship that defines the level of the transfer $L_{i,j}$ to each household through the constraint $F_{i,j}(L_{i,j}, ...) = 0$, describing national preferences. The global social planner observes the constraints $F_{i,j}$ and anticipates them when deciding about the optimal tax rates. Generally, we let F be a function of the variables of our problem. The transfer to household j in country i is determined by $F_{i,j} = F_{i,j}(L_{i,k}, a_{l,m}(\tau_l), \tau_i) = 0$. The determining variables are: (i) the transfer levels $L_{i,k}$ of all households of country i, (ii) the abatement levels of all households, (iii) the tax level τ_i of country i. After determining general results in Sections 3.1 and 3.2, we consider specific transfer in Section 3.3.

Social welfare function: to obtain a socially efficient solution, we maximize a super-national social welfare function, that aggregates each households utility, with $w_{i,j}$ being the welfare weight, with the maximization anticipating national redistribution:

$$\begin{aligned} \max_{\tau_k, L_{k,l}} SWF = \sum_{i,j} & w_{i,j} \cdot u_{i,j}(I_{i,j} - \tau_i(e_{i,j} - a_{i,j}(\tau_i)) + L_{i,j} - \phi_{i,j}(a_{i,j}(\tau_i)), a) \\ \text{s.t.} \qquad & \sum_j [L_{i,j} - \tau_i \cdot (e_{i,j} - a_{i,j})] = 0, \quad \forall i, \\ & F_{i,j}(L_{i,k}, a_{l,m}(\tau_l), \tau_i) = 0, \quad \forall i, j \end{aligned} \tag{3}$$

where $a_{i,j}(\tau_i)$ is given by (2).

3 Analytical results

This section derives tax rules under different assumptions about the redistribution of the tax revenue. First, optimal taxes are analyzed when redistribution on the national level is determined by the social planner, which is equal to the representative agent assumption of Chichilnisky and Heal (1994). Second, we contrast the optimal tax rules to general second-best taxes when national redistribution takes an arbitrary form. Finally, we specify two redistribution schemes to show the influence on the tax rates in the presence of market damages.

3.1 Reproducing the Chichilnisky and Heal (1994)-result

Chichilnisky and Heal (1994) assume that each country or region can be represented by one agent, which derives utility from aggregate consumption of private goods (as one unit of consumption is equal to one unit of production in terms of utility). They derive the Pareto Optimum by maximizing a social welfare function that aggregates individual utilities of regions by a weighted sum. This implicitly assumes that no utility can be gained by shifting the consumption good within the country/region. Since, in our model, we disaggregate each country into subnational agents, we obtain the Chichilnisky and Heal (1994)-result by allowing for optimal redistribution within the country, hence dropping the constraints $F_{i,j} = 0$ from the maximization. Chichilnisky and Heal (1994) furthermore assume that there are no transfers between countries, so the government budgets of the individual countries are given by the pollution tax revenue collected within these countries.

We find the Pareto-optimal taxes under Chichilnisky and Heal (1994) assumptions hence by solving the optimization problem:

$$\begin{aligned} \max_{\tau_i, L_{i,j}} \sum_{i,j} & w_{i,j} \cdot u_{i,j}(I_{i,j} - \tau_i(e_{i,j} - a_{i,j}(\tau_i)) + L_{i,j} - \phi_{i,j}(a_{i,j}(\tau_i)), a) \\ \text{s.t.} \qquad & \sum_j [L_{i,j} - \tau_i \cdot (e_{i,j} - a_{i,j})] = 0, \quad \forall i, \end{aligned} \tag{4}$$

The Lagrangian is:

$$\begin{aligned} \mathcal{L} = & \sum_{i,j} w_{i,j} \cdot u_{i,j}(I_{i,j} - \tau_i(e_{i,j} - a_{i,j}(\tau_i)) + L_{i,j} - \phi_{i,j}(a_{i,j}(\tau_i)), a) \\ & + \sum_i \zeta_i \left(\sum_j [L_{i,j} - \tau_i \cdot (e_{i,j} - a_{i,j})] \right) \end{aligned} \tag{5}$$

The government's first-order conditions are:

$$\begin{aligned} 0 = \frac{\partial \mathcal{L}}{\partial \tau_p} = \sum_{i,j} w_{i,j} MUA_{i,j} & \underbrace{\frac{\partial a}{\partial \tau_p}}_{\sum_l \frac{\partial a_{p,l}}{\partial \tau_p}} \\ & + \sum_j w_{p,j} (MUC)_{p,j} \left[-(e_{i,j} - a_{i,j}) + \tau_p \frac{\partial a_{p,j}}{\partial \tau_p} - \underbrace{\phi'_{p,j}}_{=\tau_p} \frac{\partial a_{p,j}}{\partial \tau_p} \right] \\ & - \zeta_i \left[\sum_l (e_{i,l} - a_{i,l}) - \tau_i \sum_l \frac{\partial a_{i,l}}{\partial \tau_i} \right] \end{aligned} \tag{6}$$

and

$$0 = \frac{\partial \mathcal{L}}{\partial L_{p,q}} = w_{p,q} MUC_{p,q} + \zeta_p \tag{7}$$

Here, $(MUC)_{i,j} = \frac{\partial u_{i,j}}{\partial c_{i,j}}$ are the marginal utilities of consumption and $(MUA)_{i,j} = \frac{\partial u_{i,j}}{\partial a}$ are marginal utilities of abatement of household j in country i. From the last equation we see that weighted marginal consumptions $w_{p,q}(MUC)_{p,q}$ are equalized for the households in each country p.
We can rearrange Equation (6) to give the Chichilnisky and Heal (1994)-expression for the optimal tax rate:

$$\tau_p^{\mathrm{CH}} = \frac{\sum_{i,j} w_{i,j} MUA_{i,j}}{w_{p,q}(MUC)_{p,q}}, \qquad \forall\, q \text{ in country } p. \tag{8}$$

Hence, as in Chichilnisky and Heal (1994), the marginal costs of abatement in general differ between countries since they exhibit different weighted marginal utilities of consumption $w_{i,j} MUC_{i,j}$. As a consequence, poorer countries with a higher marginal utility of consumption have a lower optimal tax rate if their aggregate weight is at least as high as that of richer countries.

3.2 Optimal Climate Policy under National Redistribution and Market Damages

In this subsection we account for redistribution on the national level, and thus add the constraints $F_{i,j} = 0$ to the optimization of the social planner. The second-best tax rates are obtained by the following optimization procedure:

$$\begin{aligned} &\max_{\tau_i} \sum_{i,j} w_{i,j} \cdot u_{i,j}(I_{i,j} - \tau_i(e_{i,j} - a_{i,j}(\tau_i)) + L_{i,j} - \phi_{i,j}(a_{i,j}(\tau_i)), a). \\ &\quad \text{s.t.} \qquad \sum_j [L_{i,j} - \tau_i \cdot (e_{i,j} - a_{i,j})] = 0, \quad \forall i \\ &\quad \text{and} \qquad F_{i,j}(L_{i,k}, a_{l,m}(\tau_l), \tau_i) = 0, \quad \forall i, j. \end{aligned} \tag{9}$$

The Lagrangian reads:

$$\begin{aligned} \mathcal{L} = &\sum_{i,j} w_{i,j} \cdot u_{i,j}(I_{i,j} - \tau_i(e_{i,j} - a_{i,j}(\tau_i)) + L_{i,j} - \phi_{i,j}(a_{i,j}(\tau_i)), a) \\ &+ \sum_i \zeta_i \sum_j [L_{i,j} - \tau_i \cdot (e_{i,j} - a_{i,j})] + \sum_{i,j} \psi_{i,j} F_{i,j}(L_{i,k}, a_{l,m}(\tau_l), \tau_i). \end{aligned} \tag{10}$$

The government's first-order condition exhibits the same summands as in the case of optimal redistribution and some additional constraints due to the anticipation of how redistribution at the national level changes the optimal carbon tax levels, summarized in the next result.

Result 1. *If a social planner anticipates national redistribution determined by constraints $F_{i,j} = 0$, second-best tax rates are determined by :*

$$\begin{aligned}
\tau_p =& \frac{1}{-\zeta_p \sum_m \frac{\partial a_{p,m}}{\partial \tau_p}} \cdot \left(\sum_{i,j} w_{i,j} (MUA)_{i,j} \sum_m \frac{\partial a_{p,m}}{\partial \tau_p} + \sum_{i,j} \psi_{i,j} \sum_m \frac{\partial F_{i,j}}{\partial a_{p,m}} \frac{\partial a_{p,m}}{\partial \tau_p} \right. \\
&\left. + \sum_m \Psi_{p,m} \left[\sum_j (e_{p,j} - a_{p,j}) \frac{\partial F_{p,m}}{\partial L_{p,j}} + \frac{\partial F_{p,m}}{\partial \tau_p} \right] \right) \\
\zeta_p =& - w_{p,j} MUC_{p,j} - \sum_l \psi_{p,l} \frac{\partial F_{p,l}}{\partial L_{p,j}} \quad \forall j \\
=& \frac{1}{h_p} \sum_j \left(-w_{p,j} MUC_{p,j} - \sum_l \psi_{p,l} \frac{\partial F_{p,l}}{\partial L_{p,j}} \right)
\end{aligned} \tag{11}$$

with h_p being the number of households in country p.

Proof. The first order conditions are.

$$\begin{aligned}
0 = \frac{\partial \mathcal{L}}{\partial \tau_p} = \sum_{i,j} w_{i,j} MUA_{i,j} & \underbrace{\frac{\partial a}{\partial \tau_p}}_{\sum_l \frac{\partial a_{p,l}}{\partial \tau_p}} \\
& + \sum_j w_{p,j} (MUC)_{p,j} \left[-(e_{p,j} - a_{p,j}) + \tau_p \frac{\partial a_{p,j}}{\partial \tau_p} - \underbrace{\phi'_{p,j}}_{=\tau_p} \frac{\partial a_{p,j}}{\partial \tau_p} \right] \\
& - \zeta_p \left[\sum_l (e_{p,l} - a_{p,l}) - \tau_p \sum_l \frac{\partial a_{p,l}}{\partial \tau_p} \right] \\
& + \sum_{i,j} \psi_{i,j} \sum_m \frac{\partial F_{i,j}}{\partial a_{p,m}} \frac{\partial a_{p,m}}{\partial \tau_p} + \sum_m \psi_{p,m} \frac{\partial F_{p,m}}{\partial \tau_p}
\end{aligned} \tag{12}$$

$$0 = \frac{\partial \mathcal{L}}{\partial L_{p,q}} = w_{p,q} MUC_{p,q} + \zeta_p + \sum_l \psi_{p,l} \frac{\partial F_{p,l}}{\partial L_{p,q}} \tag{13}$$

Equations (12) and (13) can be rearranged to obtain the expression for second-best tax rates τ_p. □

This expression for second-best taxes differs notably from Equation (8). There are two drivers of this difference:

1. The numerator has two additional summands to the internalization of the externality that account for the distributional decision of national governments. The first summand takes account of how changes in the

abatement levels of all countries affects national redistribution, which changes the valuation of an additional unit of global abatement. Note that the optimal tax rate in country p is generally influenced by the distributional decision in all other countries i. The second summand takes account of the distributional decision within country p itself.

2. Since marginal utilities of consumption are not equalized between households, the denominator takes account of these differences by taking the average across all households.

At this point, it is difficult to gain further insight into how the optimal tax rates change for general redistribution schemes. The next section therefore considers two specific schemes.

3.3 Optimal taxes under two specific national redistribution schemes

This section looks at two redistribution rules at the subnational level. In the first scheme, households receive a transfer that matches the exact amount they paid in taxes. This scheme mimics a common assumption in the literature (for example command and control regulation). In the second scheme, redistribution is based on a national welfare function which aggregates households in each country, hence a national social planner endogenously decides on redistribution.

We find that the rules for second-best taxes differ considerably between both approaches, as expected, and that the shape of the utility function, level and distribution of damages and costs as well as heterogeneity in income levels across and within countries influence tax rates. Further, if redistribution is based on a national welfare function and market damages are present, changes in tax rates to the case when redistribution is optimal are only moderate in magnitude. Most importantly, while the tax rates under optimal and national redistribution can be the same in some cases, second-best transfers may differ to a large extent to first-best transfers.

3.3.1 Transfer rule 1: Reimbursements of taxes

If we set the redistribution rule such that households expenses in taxes are fully reimbursed by the national government (or climate policy is implemented for example through command and control without further redistribution) the constraints become:

$$F_{i,j}(a_{l,m}(\tau_l), L_{i,k}, \tau_i) = L_{i,j} - \tau_i \cdot (e_{i,j} - a_{i,j}) = 0.$$

We can determine all terms in Equation (11):

$$\begin{aligned} \frac{\partial F_{i,j}}{\partial a_{p,m}} &= \begin{cases} \tau_p & i = p, j = m \\ 0 & \text{else} \end{cases} \\ \frac{\partial F_{p,m}}{\partial \tau_p} &= -(e_{p,m} - a_{p,m}) \\ \frac{\partial F_{p,m}}{\partial L_{p,q}} &= \begin{cases} 1 & m = q \\ 0 & \text{else} \end{cases} \end{aligned} \tag{14}$$

to derive a rule for the optimal taxes in all countries:

$$\tau_p = \frac{\sum_{i,j} w_{i,j} (MUA)_{i,j} \sum_m \frac{\partial a_{p,m}}{\partial \tau_p}}{\sum_j w_{p,j} MUC_{p,j} \frac{\partial a_{p,j}}{\partial \tau_p}}. \tag{15}$$

The second-best tax rates look similar to the optimal case τ_p^{CH} under optimal national redistribution in equation (8), but can, as we will see, turn out to be quite different in magnitude.
These differences in magnitude infer from differences in the denominator: As opposed to equalized marginal utilities of consumption for each country as in the Chichilnisky and Heal (1994)-case, the denominator in Equation (15) contains a sum of weighted marginal utilities of consumption, each multiplied with a measure of the costs of abatement born by each household. The multiplier can be derived from equation (2) through the implicit function theorem: $\frac{\partial a_{p,m}}{\partial \tau_p} = \left(\partial^2 \phi_{p,m} / \partial a_{p,m}^2\right)^{-1}$. Hence, if households with higher weighted marginal utilities of consumption have steeper marginal abatement costs, the denominator becomes smaller and the optimal tax becomes larger (all else equal).

In the following we assume that abatement costs are equal across households. We further consider only market damages, meaning that the utility function takes the following form: $u_{i,j}(c_{i,j}, a) = u_{i,j}(c_{i,j} + b_{i,j}(a))$, where $b_{i,j}(a)$ are the benefits derived from abatement. Under these assumptions, we can derive the following result:

Result 2. *Assume that abatement costs and damages are equal across households and that there are only market damages. Then, second-best tax rates in the case of transfer scheme 1 (i.e. when transfers reimburse tax payments) differ from when redistribution is optimal. We find:*

i If the social planner increases the weight of a household with a high marginal utility of consumption and decreases the weight of a household with a low marginal utility of consumption (i.e. the social planner has a larger inequality aversion), the change in second-best tax rates increases in the difference in marginal utility of consumption between the *two households. If the other $N-1$ countries have the same distribution of income, the social cost of carbon of the first country decreases and of the other $N-1$ countries increases.*

ii *If the concavity of the utility function of the households is close to zero, second-best tax differ only moderately from the first-best.*

Proof. Under the assumptions of Result 2 Equation (15) becomes:

$$\tau_p = \frac{\sum_{i,j} w_{i,j}(MUC)_{i,j}\frac{\partial b}{\partial a}}{\frac{1}{h_p}\sum_j w_{p,j}(MUC)_{p,j}}. \tag{16}$$

This set of N equations determines the values for the SCC τ_p. Take a specific country k and two households q and r. If we increase the weight of household q by ε, $\tilde{w}_{kq} = w_{kq} + \varepsilon$, and decrease the weight of r by ε, $\tilde{w}_{kr} = w_{kr} - \varepsilon$ (leaving all other weights at their old value $\tilde{w}_{ij} = w_{ij}$), the system of equations above defines the new SCCs. The implicit function theorem defines the rate of change. For this purpose, rewrite the above equations as

$$G_p = \tau_p \cdot \sum_j \tilde{w}_{p,j}(MUC)_{p,j} - h_p\frac{\partial b}{\partial a}\sum_{i,j}\tilde{w}_{i,j}(MUC)_{i,j} = 0$$

. We can then write down the implicit function theorem:

$$\left(\frac{\partial G_p}{\partial \tau_i}\right)|_{\varepsilon=0}\frac{d\tau_p}{d\varepsilon} = -\frac{dG_p}{d\varepsilon}|_{\varepsilon=0} \tag{17}$$

Assuming that the inverse of matrix $\left(\frac{\partial G_k}{\partial \tau_i}\right)|_{\varepsilon=0}$ exists, we can show the first part of Result 2 by first recognizing that the inverse $\left(\frac{\partial G_k}{\partial \tau_i}\right)^{-1}|_{\varepsilon=0}$ does not depend on ε and is therefore independent of which households in which country experience a change in weights and second writing down the vector

$$\frac{dG_p}{d\varepsilon}|_{\varepsilon=0} = (MUC_{kq} - MUC_{kr})\begin{cases}\tau_k - h_k\frac{\partial b}{\partial a} & p = k\\ -h_p\frac{\partial b}{\partial a} & p \neq k\end{cases} \tag{18}$$

Hence the change in SCCs for all countries is directly proportional to the difference in marginal utilities of consumption of the two households, hence the inequality in country k:

$$\frac{d\tau_p}{d\varepsilon} = (MUC_{kq} - MUC_{kr})\cdot C_{p;k} \tag{19}$$

The constant $C_{p;k}$ does not depend on which households' weights change, hence (i) the change of SCC is larger with larger difference in consumption between the households q and r, (ii) if the difference in consumption of the households changes sign, so do the changes in SCC of all countries.

We now turn to the sign of changes in the SCCs. We first show that there is at least one country with a positive change $\frac{d\tau_p}{d\varepsilon} \geq 0$ and one with a negative change $\frac{d\tau_p}{d\varepsilon} \leq 0$. If we multiply equation (16) with $\frac{1}{h_p}\sum_j w_{p,j}(MUC)_{p,j}$, take the derivative with respect to ε and sum over p, we get:

$$\frac{d}{d\varepsilon}\sum_p \frac{\tau_p}{h_p}\left(\sum_j w_{p,j}(MUC)_{p,j}\right)^2 = \frac{d}{d\varepsilon}\frac{\partial b}{\partial a}\left(\sum_{i,j} w_{i,j}(MUC)_{i,j}\right)^2 \tag{20}$$

$$\Leftrightarrow \sum_p \frac{\frac{d}{d\varepsilon}\tau_p}{h_p}\left(\sum_j w_{p,j}(MUC)_{p,j}\right)^2$$

$$= \frac{\partial^2 b}{\partial a^2}\frac{da}{d\varepsilon}\sum_p \frac{\tau_p}{h_p}\sum_j w_{p,j}(MUC)_{p,j}\left(\sum_{i,j} w_{i,j}(MUC)_{i,j}\right)^2$$

$$+ \quad 2\sum_p \left[\underbrace{\tau_p \frac{\sum_j w_{p,j}(MUC)_{p,j}}{h_p} - \frac{\partial b}{\partial a}\sum_{i,j} w_{i,j}(MUC)_{i,j}}_{=0}\right]\frac{d}{d\varepsilon}\sum_j w_{p,j}(MUC)_{p,j}$$

When expressing the change in total abatement when changing the weights as $\frac{da}{d\varepsilon} = \sum_i h_i \frac{\partial a_{ij}}{\partial \tau_i}\frac{d}{d\varepsilon}\tau_i$, the last equation becomes

$$\sum_p \frac{d\tau_p}{d\varepsilon}\underbrace{\frac{\left(\sum_j w_{p,j}(MUC)_{p,j}\right)^2}{h_p}}_{>0} = \underbrace{\frac{\partial^2 b}{\partial a^2}}_{\leq 0}\sum_i \underbrace{h_i \frac{\partial a_{ij}}{\partial \tau_i}}_{>0}\frac{d\tau_i}{d\varepsilon}\underbrace{\left(\sum_{i,j} w_{i,j}(MUC)_{i,j}\right)^2}_{>0} \tag{21}$$

The last equation shows that the changes in SCC $\frac{d\tau_p}{d\varepsilon}$ cannot all be of the same sign.

Let us now assume we have $N-1$ countries that are identical, i.e. if we sort all households in ascending order of their income we have $I_{i,j} = I_{p,j},\ \forall i,p,\ \forall j$. Due to this symmetry, these $N-1$ countries will have the same SCC $\tau_i = \tau_p$ and we can treat them as one country. As shown above, either country $k's$ SCC decrease and the SCC of all other countries increases or v.v..

We show that the former is true by assuming the opposite to be the case: $\frac{d\tau_k}{d\varepsilon} > 0$ and $\frac{d\tau_p}{d\varepsilon} < 0\ \forall p \neq k$. In this case, the sum of weighted marginal utilities of consumption in country k, $\sum_j w_{k,j}(MUC)_{p,j}$, has to increase when changing the weights because (i) given a fixed set of taxes, the social planner puts more weight on a household with higher marginal utility of consumption and a lower weight on a household with lower marginal utility of consumption, which increases the sum, and (ii) as country k contributes more to the public good while the other countries contribute less and its tax rate is above $h_k \frac{\partial b}{\partial a}$, the sum of consumption and benefits decrease for every household in country k, which increases the sum of weighted marginal utilities of consumption.

On the other hand, the sum of weighted marginal utilities of consumption of the other $N-1$ countries decreases as consumption for each household increases: country k contributes more to the public good and all other countries can decrease their contribution while still having a tax rate τ_p above $(N-1)h_k \frac{\partial b}{\partial a}$ due to equation (16). In this case the aggregate consumption increases:

$$b(\tilde{a}_k + (N-1)\tilde{a}_p) - \phi\left(\frac{\tilde{a}_p}{h_p}\right) \geq b(a_k + (N-1)\tilde{a}_p) - \phi\left(\frac{\tilde{a}_p}{h_p}\right) \tag{22}$$

$$\underbrace{\geq b(a_k + (N-1)a_p) - \phi\left(\frac{a_p}{h_p}\right)}_{\forall \tau_p \frac{d\phi(a_{pj})}{da_{pj}} > (N-1)h_k \frac{\partial b}{\partial a} \text{ and } \tilde{a}_p < a_p}, \tag{23}$$

where $\tilde{}$ indicates values with changed weights. Hence, the sum of weighted marginal utilities of all identical $N-1$ countries decreases.

Since $\tau_k = h_k \frac{\partial b}{\partial a}\left(1 + \frac{\sum_{i \neq k,j} w_{i,j}(MUC)_{i,j}}{\sum_j w_{k,j}(MUC)_{k,j}}\right)$ and the the summand in the bracket decreases, $\frac{\partial b}{\partial a}$ would have to increase so that $\frac{\partial \tau_k}{\partial \varepsilon} > 0$. In this case, however, $\tau_p = h_p \frac{\partial b}{\partial a}\left((N-1) + \frac{w_{k,j}(MUC)_{i,k}}{\sum_j w_{p,j}(MUC)_{p,j}}\right)$ increases as the second summand increases. Hence the assumption that $\frac{\partial \tau_k}{\partial \varepsilon} > 0$ cannot be true and we have $\frac{\partial \tau_k}{\partial \varepsilon} < 0$ and $\frac{\partial \tau_p}{\partial \varepsilon} > 0$ if inequality aversion of the social planner increases.

We next show that the deviation of second-best and first-best tax rates goes to zero as the concavity of the utility functions $u_{i,j}$ goes to zero. For the assumptions of Result 2 the Chichilnisky and Heal (1994)-tax rule can be written as:

$$\tau_p^{\text{CH}} = \frac{\partial b}{\partial a} \frac{\sum_i h_i w_{i,j}(MUC)_{i,j}}{w_{p,j}(MUC)_{p,j}}. \tag{24}$$

The ratio of second best taxes in equation (16) to first-best taxes than becomes:

$$\frac{\tau_p}{\tau_p^{\text{CH}}} = \frac{\frac{\partial b}{\partial a}}{\frac{\partial b^{\text{CH}}}{\partial a}} \frac{\left(\frac{\sum_{i,j} w_{i,j}(MUC)_{i,j}}{\sum_i h_i w_{i,m}(MUC)_{i,m}^{\text{CH}}}\right)}{\left(\frac{\frac{1}{h_p}\sum_j w_{p,j} MUC_{p,j}}{w_{p,m}(MUC)_{p,m}^{\text{CH}}}\right)} \tag{25}$$

The ratio in the denominator is the difference between the average of weighted marginal utilities of consumption under second-best redistribution $\frac{1}{h_p}\sum_j w_{p,j} MUC_{p,j}$ to the case when weighted marginal utilities of consumption are equalized

$w_{p,m}(MUC)^{\text{CH}}_{p,m}$ in country p. The ratio in the numerator is the difference in the sum of the total levels of weighted marginal utilities of consumption between the second-best and the Chichilnisky and Heal (1994)-case on a global level. These differences are determined by the concavity of the utility function. If the concavity goes to zero, both terms do not differ from each other. □

Result 3. *Assume that abatement costs are equal across households and that there are only market damages. If damages disproportionally affect households with a high weighted marginal utility of consumption, differences in tax rates between the second-best and the optimal redistribution case become more pronounced.*

Proof. For result 3, we take a specific country p, assume two households and change the distribution of constant marginal damage function: $b_{p,1} = z \cdot a$, $b_{p,2} = (1 - z) \cdot a$. Second-best taxes are:

$$\tau_p = \frac{\sum_{i \neq p,j} w_{i,j}(MUC)_{i,j}\frac{\partial b_{i,j}}{\partial a} + w_{p,1}MUC_{p,1} \cdot z + w_{p,2}MUC_{p,2} \cdot (1 - z)}{\frac{1}{h_p}\sum_j w_{p,j}(MUC)_{p,j}}. \tag{26}$$

If $z = 1$, household 2 does not experience any damages. If household 1 is rich, the weight $w_{p,1}MUC_{p,1}$ that translates market damages to damages in social welfare is relatively low. However, the poorer household 1 is, the higher the weight with which its market damages are valued in the social welfare function and the higher the tax rate. Second-best tax rates increase for all countries with the internalization of damages for the specific household. □

Result 2 and 3 show that inequality critically determines second-best internalization of the global externality through two main channels. First, the deviation of second-best taxes from the Chichilnisky and Heal (1994)-case is determined by concavity of the utility function in combination with the distribution of wealth across and within countries. Second, if the distribution of damages is heterogeneous among households, second-best taxes can change crucially in all countries: As there is no compensation to poor households for damage or abatement costs, the social planner has an increased incentive to raise second-best taxes in all countries to limit the decrease in utility of poor households if they experience large damages.

3.3.2 National government redistributes according to a national welfare function

In this section, the national government chooses transfers to households based on a national welfare function (NWF). This welfare function aggregates the utilities of each household through a weighted sum. The redistributional constraint $F_{i,j}$ is given by

$$F_{i,j}(a_{l,m}(\tau_l), L_{i,k}, \tau_i) = \frac{\partial NWF}{\partial Li, j} - \frac{\partial NWF}{\partial Li, m_i} = \Omega_{i,j} MVC_{i,j} - \Omega_{i,m_i} MVC_{i,m_i} = 0$$

for an arbitrary household m_i in country i, $\Omega_{i,j}$ are the welfare weights the national government assigns to each household and $MVC_{i,j}$ are the marginal utilities of consumption for a utility function of each household given by $v_{i,j}(c_{i,j}, a)$.[1]

The derivatives of $F_{i,j}$ with respect to $a_{p,m}$, τ_p, and $L_{p,j}$ are given by:

$$\begin{aligned}
\frac{\partial F_{i,j}}{\partial a_{p,m}} &= \Omega_{i,j} \frac{\partial MVC_{i,j}}{\partial a} - \Omega_{i,m_p} \frac{\partial MVC_{i,m_p}}{\partial a} \\
\frac{\partial F_{p,m}}{\partial \tau_p} &= -\Omega_{p,m} \frac{\partial MVC_{p,m}}{\partial c_{p,m}} (e_{p,m} - a_{p,m}) + \Omega_{p,m_p} \frac{\partial MVC_{p,m_p}}{\partial c_{p,m_p}} (e_{p,m_p} - a_{p,m_p}) \\
\frac{\partial F_{p,m}}{\partial L_{p,j}} &= \begin{cases} \Omega_{p,m} \frac{\partial MVC_{p,m}}{\partial c_{p,m}} & j = m \neq m_p \\ -\Omega_{p,m_p} \frac{\partial MVC_{p,m_p}}{\partial c_{p,m_p}} & j = m_p \neq m \\ 0 & \text{else} \end{cases} .
\end{aligned} \tag{28}$$

Inserting these expressions into Equation (11) yields the following second-best tax rule (see Appendix B for details):

$$\zeta_p = -\frac{\sum_j \frac{w_{p,j} MUC_{p,j}}{\Omega_{p,j} MMVC_{p,j}}}{\sum_j \frac{1}{\Omega_{p,j} MMVC_{p,j}}} \tag{29}$$

and

$$\tau_p = \frac{1}{\zeta_p} \left(-\sum_{i,j} w_{i,j} MUA_{i,j} + \sum_{i,j} (w_{i,j} MUC_{i,j} + \zeta_i) \frac{MVCA_{i,j}}{MMVC_{i,j}} \right). \tag{30}$$

[1]Let utility $v_{i,j}(c_{i,j}, a)$ be defined as in Section 2, with utility function $v_{i,j}$ defining how the national government of country i values consumption and abatement for each of its households j. For an exogenously given environmental tax τ_i, the national government faces the following optimization problem:

$$\max_{l_{i,j}} NWF = \sum_j \Omega_{i,j} \cdot v(c_{i,j}, a) \qquad \text{s.t.} \qquad \sum_j l_{i,j} = \tau_i \sum_j (e_{i,j} - a_{i,j}),$$

which translates into the following Lagrangian:

$$\mathcal{L} = \sum_j \Omega_{i,j} \cdot v(c_{i,j}, a) - \xi_i \left(\sum_j L_{i,j} - \tau_i \sum_j (e_{i,j} - a_{i,j}) \right).$$

Setting $\partial \mathcal{L} / \partial L_{k,m} = 0$ we get the following first-order condition:

$$\xi_k = \Omega_{k,m} MVC_{k,m}. \tag{27}$$

By choosing an arbitrary household of each country m_i, equations (27) can be reduced to $\Omega_{i,j} MVC_{i,j} - \Omega_{i,j} MVC_{i,m_i} = 0$.

These expressions lead to the following insights.

Result 4. *If the welfare weights in the national and the supernational social welfare functions are identical, the Chichilnisky and Heal (1994) case is reproduced.*

Proof. Assume that $\Omega_{i,j} = w_{i,j} = \hat{w}_{i,j}$. From Equation (29) then follows that $\zeta_p = -\hat{w}_{p,m} MUC_{p,m}$ for all m. The terms involving $\sum_j \frac{1}{\Omega_{p,j} MMVC_{p,j}}$ cancel out because $\hat{w}_{k,m} MUC_{k,m}$ is constant within each country and can be pulled out of the sum. Inserting this expression into Equation (30) yields:

$$\tau_p = \frac{\sum_{i,j} \hat{w}_{i,j} MUA_{i,j}}{\hat{w}_{p,j} MUC_{p,j}}$$

which is equivalent to Equation (8). □

We now turn to the case of an isoelastic utility function.

Result 5. *If the utility function is isoelastic and only market damages occur, that is*

$$u_{i,j} = v_{i,j} = \begin{cases} \frac{(c_{i,j}+b_{i,j}(a))^{1-\eta}-1}{1-\eta} & \eta < 1 \\ \log(c_{i,j} + b_{i,j}(a)) & \eta = 1 \end{cases},$$

the second-best tax rule depends crucially on η:

i *if $\eta = 1$ the second-best tax rule is equal to the Chichilnisky and Heal (1994) case treated in Section 3.1, irrespective of redistribution at the national level.*

ii *if $\eta < 1$ the second-best tax rule depends on the level of η and on the between-country distribution of the national aggregate of consumption and damages. It does not directly depend on the distribution of damages among households within one country.*

We start the proof by deriving the tax rule for the second, more general case. Then we derive the more specific result for a logarithmic utility function by setting $\eta = 1$.

Proof. Regarding case *ii*, simply deriving marginal utilities of abatement and consumption and inserting them into Equations (29) and (30) yields:

$$\tau_p = \frac{\sum_m (c_{p,m} + b_{p,m}(a))}{\sum_l w_{p,l}(c_{p,l} + b_{p,l}(a))^{(1-\eta)}} \cdot \sum_i \frac{\sum_l w_{i,l}(c_{i,l} + b_{i,l}(a))^{(1-\eta)}}{\sum_m (c_{i,m} + b_{i,m}(a))} \sum_j \frac{\partial b_{i,j}}{\partial a} \tag{31}$$

The equation shows that marginal market damages enter the second-best tax rule only in the sum $\sum_j \frac{\partial b_{i,j}}{\partial a}$. Heterogeneous damages on the household

level in one country hence influence the tax level only through changes in marginal utilities of consumption.
For this specification of the utility function the optimal tax rule from Equation (8) becomes:

$$\tau_p^{\mathrm{CH}} = \frac{(c_{p,l}^{\mathrm{CH}} + b_{p,l}(a^{\mathrm{CH}}))}{w_{p,l}(c_{p,l}^{\mathrm{CH}} + b_{p,l}(a^{\mathrm{CH}}))^{(1-\eta)}} \sum_i \frac{w_{i,l}(c_{i,l}^{\mathrm{CH}} + b_{i,l}(a^{\mathrm{CH}}))^{1-\eta}}{(c_{i,l}^{\mathrm{CH}} + b_{i,l}(a^{\mathrm{CH}}))} \sum_j \frac{\partial b_{i,j}}{\partial a} \tag{32}$$

For case *ii* we therefore compare equalized weighted marginal utilities of consumption, $\frac{(c_{p,l}^{\mathrm{CH}}+b_{p,l}(a^{\mathrm{CH}}))}{w_{p,l}(c_{p,l}^{\mathrm{CH}}+b_{p,l}(a^{\mathrm{CH}}))^{(1-\eta)}}$, to the weighted averages $\frac{\sum_m (c_{p,m}+b_{p,m}(a))}{\sum_l w_{p,l}(c_{p,l}+b_{p,l}(a))^{(1-\eta)}}$. This is similar to the redistribution rule in the case of homogeneous damages (Result 2): η together with inequality in consumption determine in how far these two terms differ from each other (see the discussion around Figure **??**). If, however, the convexity of the marginal utility function and inequality among households is moderate, differences in tax rates will also only be moderate. In addition, the average is weighted with the share of household consumption in total consumption of the country. This can lead to further differences of second-best taxes compared to optimal redistribution. However, this effect may also counteract differences due to differentηs, depending on second-best compared to first-best redistribution. This proves part *ii* of the result.
Regarding the proof of part *i*, it suffices to set $\eta = 1$ in Equation (32) to obtain the following second-best tax rule:

$$\tau_p = \frac{\sum_l c_{p,l} + b_{p,l}(a)}{\sum_l w_{p,l}} \sum_i \frac{\sum_m w_{i,m}}{\sum_l (c_{i,l} + b_{i,l}(a))} \sum_j \frac{\partial b_{i,j}}{\partial a}. \tag{33}$$

Accordingly, the optimal tax rule for the Chichilnisky and Heal case becomes:

$$\tau_p^{\mathrm{CH}} = \frac{c_{p,l}^{\mathrm{CH}} + b_{p,l}(a^{\mathrm{CH}})}{w_{p,l}} \sum_i \frac{w_{i,l}}{c_{i,l}^{\mathrm{CH}} + b_{i,l}(a^{\mathrm{CH}})} \sum_j \frac{\partial b_{i,j}}{\partial a} \tag{34}$$

Since in the Chichilnisky and Heal case redistribution is optimal, the welfare weight times the marginal utility of consumption is constant within countries, that is $w_{p,l}/(c_{p,l}^{\mathrm{CH}} + b_{p,l}(a^{\mathrm{CH}})) = \zeta_p, \ \forall\ l$. It follows that $w_{p,l}/(c_{p,l}^{\mathrm{CH}} + b_{p,l}(a^{\mathrm{CH}})) = \sum_m w_{p,m} / \sum_m (c_{p,m}^{\mathrm{CH}} + b_{p,m}(a^{\mathrm{CH}}))$. Inserting this equality into the last equation demonstrates that both tax rules are identical. Redistribution on the national level does hence not change the tax rates compared to the case of representative agents if the utility function is logarithmic and only market damages are considered. This proves part *i* of the result.

□

Part i of this result is remarkable since the second-best tax rates are equal to the optimal rates, but the actual transfers to households can differ substantially from the optimal transfers, depending on the difference between $w_{i,j}$ and $\Omega_{i,j}$. The intuition behind this result follows from the determination of redistribution at the national level. The national government will equalize weighted (with Ω) marginal utility of consumption, which, due to the assumption of market damages, is equal to the sum of consumption and damages. If the social planner were able to increase the consumption level of a specific household in the direction of the planner's distributional preference by changing the tax rate, the national government would use transfers to reverse this increase in order to return to its preferred allocation of consumption. The global social planner will therefore internalize only the environmental externality, thus maximizing the size of the 'cake' irrespective of redistribution.

Regarding the second part of Result 5, differences in second-best taxes to optimal ones will be only moderate if η is moderate and heterogeneity in income is moderate. Most importantly, the distribution of damages among households does not directly lead to changes in tax rates, but only indirectly through changes in marginal utility of consumption and therefore inequality among households.

The intuition to second-best tax rates differing only moderately from first-best ones is similar to the case when $\eta = 1$. Since the national government will redistribute aggregate consumption among the households according to national preferences, the social planner tends to maximize aggregate consumption through the internalization of the environmental externality.

4 Numerical simulations

This section uses numerical methods to visualize some of the results from the previous section and to provide additional insights into the workings of our model. We analyze the most simple case in which there are two countries each inhabited by two households. Country 2 is the benchmark region in which the government is utilitarian and households receive the same levels of income. In country 1, one or more factors (such as welfare weights, the distribution of income between households, or the total income level) differ from country 2. We analyze the effect these differences have on the second-best tax rate in each country for the different national recycling schemes described in Section 3.3: (1) reimbursement of taxes and (2) optimal redistribution according to welfare weights.

In Section 4.1 we analyze the case in which all households are equally affected by climate damages. In Section 4.2 we consider the case in which households are affected differently.

We find that both, for the case of non-market and for the case of market damages, the differences between the countries have a comparatively low effect on the optimal tax rate when damages are equal across households. In the case of heterogeneous damages, the changes in optimal carbon taxes between countries becomes much more pronounced and can lead to a doubling of the optimal tax rates as compared to the conventional case described in Section 3.1.

We use the following isoelastic utility function to illustrate the case of market damages:

$$U_{i,j} = \frac{\left(c_{i,j} - \alpha \sum_{i,j}(e_{i,j} - a_{i,j})\right)^{(1-\eta)} - 1}{1-\eta}, \tag{35}$$

and the following CES utility function for the case of non-market damages:

$$U_{i,j} = \left(\theta c_{i,j}^{\rho} + (1-\theta)(\sum_{i,j} a_{i,j})^{\rho}\right)^{(1/\rho)}. \tag{36}$$

4.1 Homogenous damages

We first compare the effect of changing the inequality aversion of the social planner by changing the weights $w_{i,j}$ in favor of the poor agent in figure 1. Changes in the SCC are only moderate, especially for small η and more pronounced for the first transfer scheme.

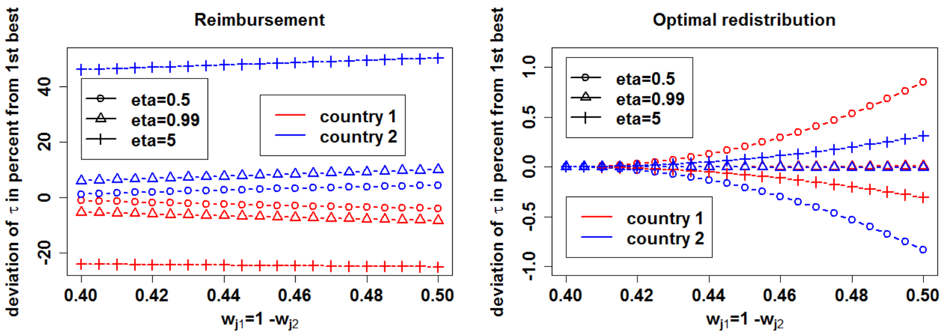

Figure 1: Comparing second-best tax rates for utility functions with each household receives what she paid in taxes (left) and redistribution of the revenues based on national preferences (right); countries differ only in their income distribution with Country 1: $Inc_{1,1}/Inc_{1,2} = 3/7$, Country 2 $Inc_{2,j} = 5$. The weights for national preferences on the right are Country 1: $\Omega_{1,1}/\Omega_{1,2} = 2/3$, Country 2: $\Omega_{2,1}/\Omega_{2,2} = 1$.

The next figures compare the changes for social welfare functions that include non-market damages. Figure 2 displays the effect of variations in the damage parameters on the optimal carbon tax rates for the case of market

and non-market damages.
It can be seen that changes in the optimal tax rate are comparatively small for transfer scheme (2) and that there are no changes for transfer scheme (1). The results remain almost unchanged when the countries additionally differ in total income, but the distribution between households within countries is equal. These findings are summarized in Figure 5 in Appendix A.
Figure 3 displays the effect on the optimal carbon tax rates when the income between households in country 1 is distributed unequally. In this case recycling through transfer scheme (2) still leads to changes in the optimal carbon tax on the same order of magnitude, while transfer scheme (1) leads to much larger changes compared to the case in which countries only differ in their welfare weights.

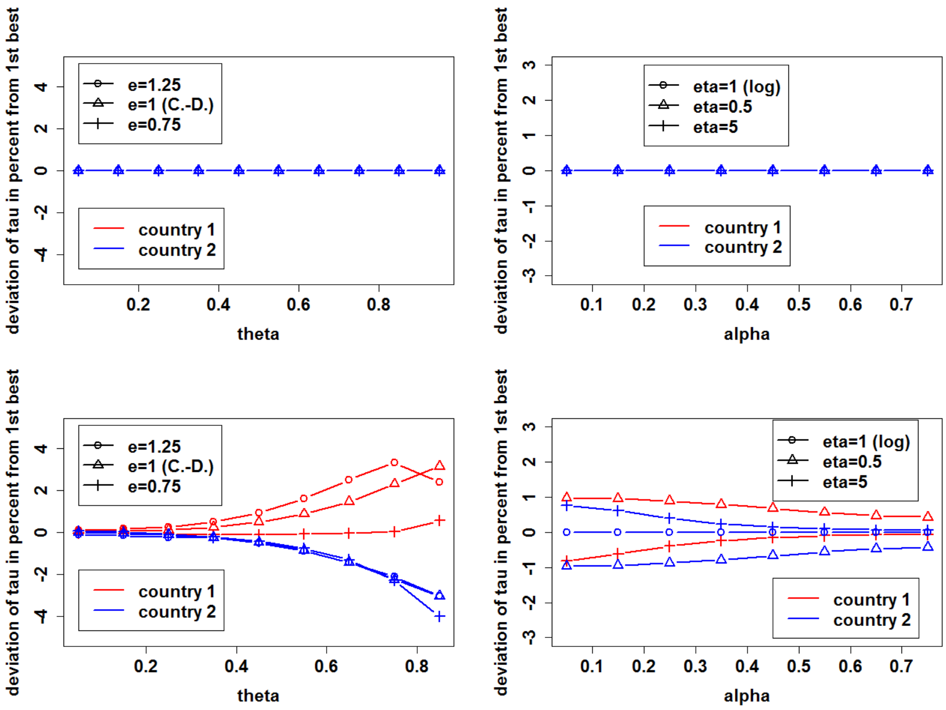

Figure 2: Comparing second-best tax rates for utility functions with non-market damages (left column) and market damages (right column) for variations in the damage parameter and for different recycling schemes. Top row: each household receives what she paid in taxes. Bottom row: redistribution of the revenues based on national preferences. For the left column we used a CES production function and for the right row an isoelastic production function. Countries differ only in their preferences for redistribution, $\Omega_{i,j}$. Country 1: $\Omega_{1,1}/\Omega_{1,2} = 2/3$, Country 2: $\Omega_{2,1}/\Omega_{2,2} = 1$, $w_{i,j} = 1$.

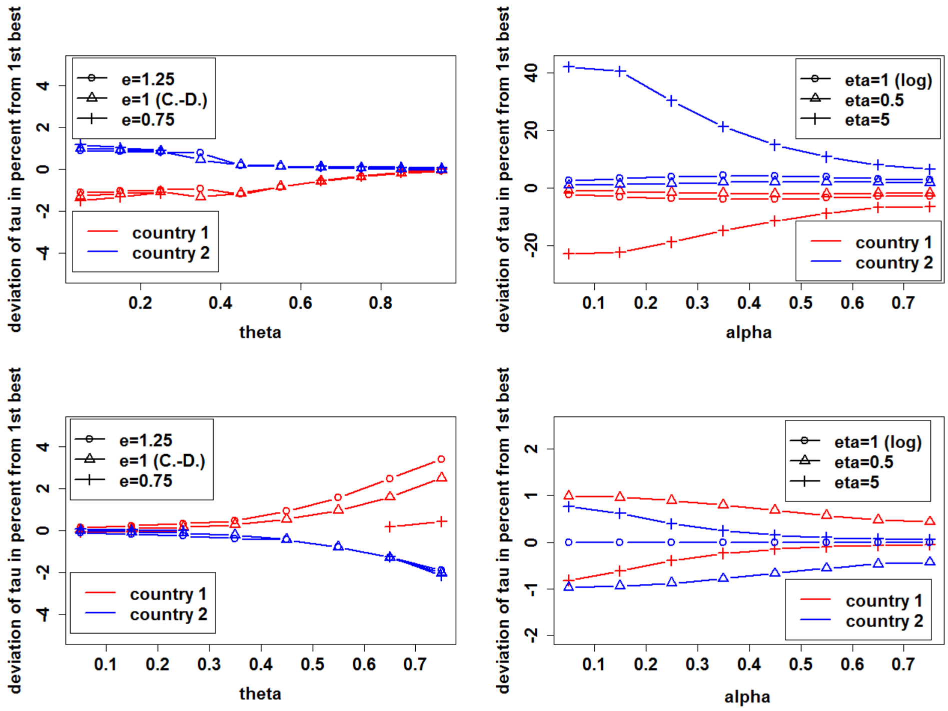

Figure 3: Comparing second-best tax rates for utility functions with non-market damages (left column) and market damages (right column) for variations in the damage parameter and for different recycling schemes. Top row: each household receives what she paid in taxes. Bottom row: redistribution of the revenues based on national preferences. For the left column we used a CES production function and for the right column an isoelastic production function. Countries differ in their preferences for redistribution, $\Omega_{i,j}$, as well as in income between households. Country 1: $\Omega_{1,1}/\Omega_{1,2} = 2/3$, $I_{1,1}/I_{1,2} = 2/3$, Country 2: $\Omega_{2,1}/\Omega_{2,2} = I_{2,1}/I_{2,2} = 1.$, $w_{i,j} = 1$.

4.2 Heterogeneous damages

This section analyzes the case when households within countries are affected differently by climate damages. We exemplify this case by using an isoelastic utility function for a given set of parameters. Further, countries differ in their welfare weights and in the distribution between households within the country. We introduce a new parameter z which stands for the share of damages going to household 1 in both countries (the remaining share, 1-z, then goes to household 2). The utility functions hence are given by:

$$U_{i,1} = \frac{1}{1-\eta}\left(c_{i,j} - z\alpha \sum i,j(e_{i,j} - a_{i,j})\right)^{(1-\eta)}, \tag{37}$$

and

$$U_{i,2} = \frac{1}{1-\eta}\left(c_{i,j} - (1-z)\alpha \sum i,j(e_{i,j} - a_{i,j})\right)^{(1-\eta)}. \tag{38}$$

Figure 4 summarizes the results. In brief: the effects of differences in the countries welfare weights and between-household income distribution on the optimal carbon tax rate are much more pronounced than in the case of homogenous damages, when the revenue is recycled through transfer scheme (1) (i.e. reimbursement, see left panel). For optimal redistribution according the welfare weights (right panel), that is transfer scheme (2), changes remain small, since the government compensates welfare losses through climate damages.

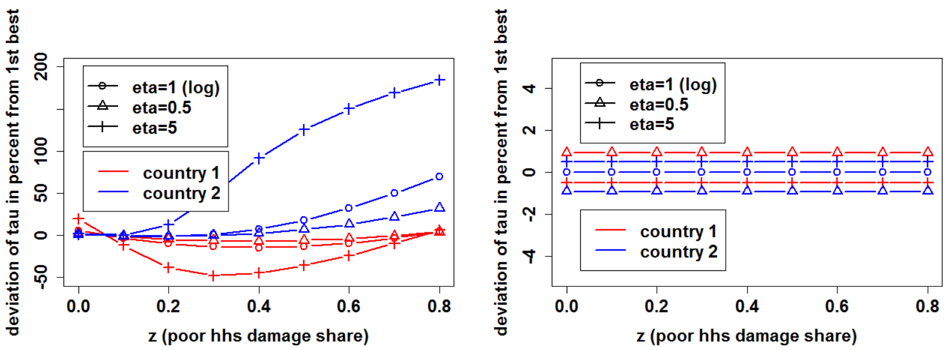

Figure 4: Comparing second-best tax rates for variations in the damages share z going to household 1 in both countries and for different recycling schemes. Left panel: each household receives what she paid in taxes. Right panel: redistribution of the revenues based on national preferences. Countries differ in their preferences for redistribution, $\Omega_{i,j}$, as well as in income between households. Country 1: $\Omega_{1,1}/\Omega_{1,2} = 2/3$, $I_{1,1}/I_{1,2} = 2/3$, Country 2: $\Omega_{2,1}/\Omega_{2,2} = I_{2,1}/I_{2,2} = 1$, $w_{i,j} = 1$.

5 Conclusion

This article calculates the social cost of carbon taking into account that countries consist of heterogeneous households headed by national, optimizing governments. Previous literature, by contrast, frequently modeled countries as single representative agents. We demonstrate that allowing for this additional level of governance leads to potentially large deviations in the social cost of carbon for each country.

Allowing for an additional level of governance leads to an information asymmetry between a global social planner, commonly used for calculating the social cost of carbon, and national governments, reminiscent of the information asymmetry arising in models of optimal income taxation with heterogeneous agents: the social planner is able to observe the distribution of climate damages, of the costs of mitigation, and of income on the country but not on the household level and must thus leave redistribution to the national regulator.

Our main findings are as follows. First, we derive analytical expressions for the social cost of carbon and demonstrate that they crucially depend on the redistribution taking place within countries. Second, we determine the magnitude of the deviation of our expression for the social cost of carbon to the case in which countries are modeled as representative households: differences are especially pronounced when national governments reimburse households only with what they paid in taxes and damages fall disproportionally on poorer households. The deviations for the other cases are also relevant but an order of magnitude smaller. Finally, we use numerical methods to determine the size of these effects over a wide range of utility functions and parameters.

These results have immediate relevance for policy makers, since the social cost of carbon are a benchmark measure for efficient climate policy. In particular, we show when assuming a national representative agent has only moderate influence on the SCC: if there are only market damages and an optimizing government redistributes between its households, also if its redistributive preferences differ from the social planner. In this case, climate policy can be separated from social policy on the international level. Vice versa, if the national government does not redistribute based on different levels of marginal utilities of households, e. g. in the absence of functioning social institutions, the SCC of every country can severely change.

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Appendices

A Numerical simulations when countries differ in income

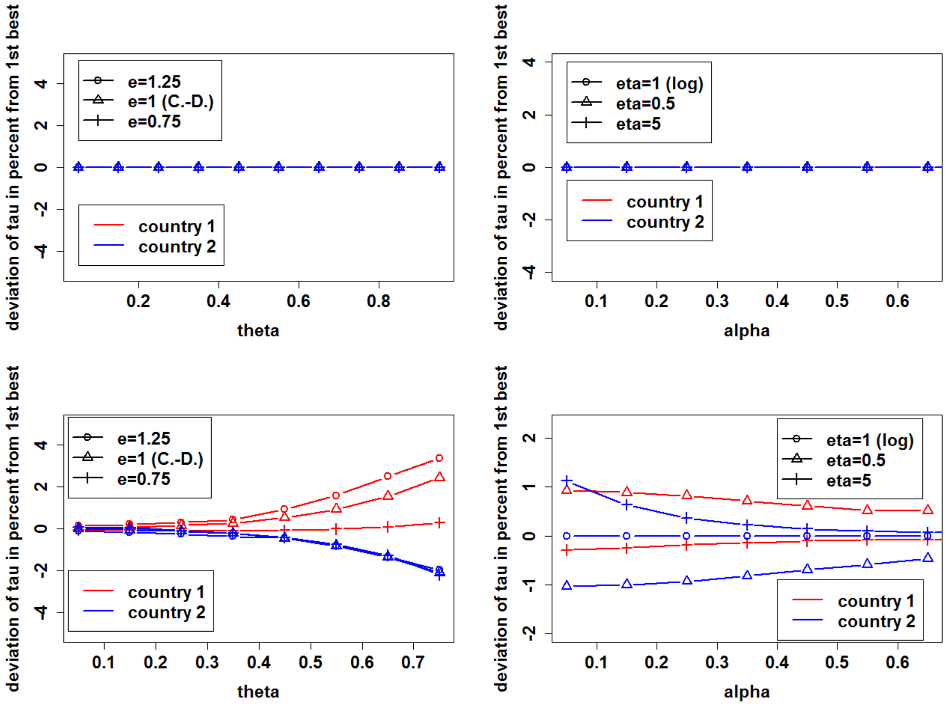

Figure 5: Comparing second best carbon tax rates for utility functions with non-market damages (left column) and market damages (right column) for variations in the damage parameter and for different recycling schemes. Top row: each household receives what she paid in taxes. Bottom row: redistribution of the revenues based on national preferences. For the left column we used a CES production function and for the right column a CRRA production function. Countries differ in their preferences for redistribution, $\Omega_{i,j}$, as well as in total income (but there are no income differences between households at the national level): $\sum_j I_{1,j}/(\sum_j I_{2,j}) = 4/5$. Country 1: $\Omega_{1,1}/\Omega_{1,2} = 2/3$, Country 2: $\Omega_{2,1}/\Omega_{2,2} = 1$, $w_{i,j} = 1$

B Derivation of the tax rule in Section 3.3.2

The respective derivatives of $F_{i,j}$ in Equation (28) are derived as follows

$$\frac{\partial F_{i,j}}{\partial a_{p,m}} = \begin{cases} (\Omega_{i,j} MVCA_{i,j} - \Omega_{i,m_i} \partial MVCA_{i,m_i}) & i \neq p \vee (i = p \wedge m \neq j \wedge m \neq m_i) \\ \left(\Omega_{p,j} MVCA_{p,j} - \Omega_{p,m_p} \partial MVCA_{p,m_p} + \Omega_{p,j} MMVC_{p,j} \underbrace{(\phi'(a_{p,j}(\tau_p), a) - \tau_p)}_{=0} \right) \\ \qquad i = p \wedge m = j \\ \left(\Omega_{p,j} MVCA_{p,j} - \Omega_{p,m_p} \partial MVCA_{p,m_p} + \Omega_{p,m_p} MMVC_{p,m_p} \underbrace{(\phi'(a_{p,m_p}(\tau_p), a) - \tau_p)}_{=0} \right) \\ \qquad i = p \wedge m = m_p \end{cases}$$

$$\frac{\partial F_{p,m}}{\partial \tau_p} = -\Omega_{p,m} \frac{\partial MVC_{p,m}}{\partial c_{p,m}} (e_{p,m} - a_{p,m}) + \Omega_{p,m_p} \frac{\partial MVC_{p,m_p}}{\partial c_{p,m_p}} (e_{p,m_p} - a_{p,m_p})$$

$$\frac{\partial F_{p,m}}{\partial L_{p,j}} = \begin{cases} \Omega_{p,m} \frac{\partial MVC_{p,m}}{\partial c_{p,m}} & j = m \neq m_p \\ -\Omega_{p,m_p} \frac{\partial MVC_{p,m_p}}{\partial c_{p,m_p}} & j = m_p \neq m \\ 0 & \text{else} \end{cases} .$$

The expression for ζ_p can be derived as follows:

$$\begin{aligned} \zeta_p &= - w_{p,j} MUC_{p,j} - \sum_l \psi_{p,l} \frac{\partial F_{p,l}}{\partial L_{p,j}} \\ &= - w_{p,j} MUC_{p,j} - \begin{cases} \Psi_{p,j} \Omega_{p,j} MMVC_{p,j} & j \neq m_p \\ -\sum_{l \neq j} \Psi_{p,l} \Omega_{p,m_p} MMVC_{p,m_p} & j = m_p \end{cases} \end{aligned}$$

For the case $j \neq m_p$ we get

$$\begin{aligned} \zeta_p &= - w_{p,j} MUC_{p,j} - \Psi_{p,j} \Omega_{p,j} MMVC_{p,j} \\ \frac{\zeta_p}{\Omega_{p,j} MMVC_{p,j}} &= - \frac{w_{p,j} MUC_{p,j}}{\Omega_{p,j} MMVC_{p,j}} - \Psi_{p,j} \qquad \Big| \sum_{j \neq m_p}, \\ \sum_{j \neq m_p} \frac{\zeta_p}{\Omega_{p,j} MMVC_{p,j}} &= - \sum_{j \neq m_p} \frac{w_{p,j} MUC_{p,j}}{\Omega_{p,j} MMVC_{p,j}} - \sum_{j \neq m_p} \Psi_{p,j}. \end{aligned} \tag{B.1}$$

The case $j = m_p$ yields:

$$\begin{aligned} \zeta_p &= -w_{p,j} MUC_{p,j} - \sum_{l \neq j} \Psi_{p,l} \Omega_{p,m_p} MMVC_{p,m_p}, \\ \frac{\zeta_p}{\Omega_{p,m_p} MMVC_{p,m_p}} &= -\frac{w_{p,j} MUC_{p,j}}{\Omega_{p,m_p} MMVC_{p,m_p}} - \sum_{l \neq j} \Psi_{p,l}. \end{aligned} \tag{B.2}$$

Adding up Equations (B.1) and (B.2) yields Equation (29).

For the derivation of an explicit expression for τ_p equivalent to Equation (30) we need the following three terms:

$$\begin{aligned}
&\sum_j (e_{p,j} - a_{p,j}) \sum_m \Psi_{p,m} \frac{\partial F_{p,m}}{\partial L_{p,j}} \\
&= \sum_j (e_{p,j} - a_{p,j}) \begin{cases} \Psi_{p,j} \Omega_{p,j} MMVC_{p,j} & j \neq m_p \\ -\sum_{l \neq j} \Psi_{p,l} \Omega_{p,m_p} MMVC_{p,m_p} & j = m_p \end{cases} \\
&= \sum_{j \neq m_p} (e_{p,j} - a_{p,j}) \Psi_{p,j} \Omega_{p,j} MMVC_{p,j} - (e_{p,j} - a_{p,j}) \Omega_{p,m_p} MMVC_{p,m_p} \sum_{l \neq m_p} \Psi_{p,l}.
\end{aligned} \tag{B.3}$$

$$\begin{aligned}
&\sum_m \psi_{p,m} \frac{\partial F_{p,m}}{\partial \tau_p} \\
&= -\sum_m \Psi_m \Omega_{p,m} \frac{\partial MVC_{p,m}}{\partial c_{p,m}} (e_{p,m} - a_{p,m}) + (e_{p,m_p} - a_{p,m_p}) \Omega_{p,m_p} \frac{\partial MVC_{p,m_p}}{\partial c_{p,m_p}} \sum_m \Psi_m.
\end{aligned} \tag{B.4}$$

$$\begin{aligned}
&\sum_{i,j} \psi_{i,j} \sum_m \frac{\partial F_{i,j}}{\partial a_{p,m}} \frac{\partial a_{p,m}}{\partial \tau_p} \\
&= \sum_{i,j} \Psi_{i,j} \left(\Omega_{i,j} MVCA_{i,j} - \Omega_{i,m_i} MVCA_{i,m_i} \right) \\
&= \sum_{i,j \neq m_i} \Psi_{i,j} \left(\Omega_{i,j} MVCA_{i,j} \right).
\end{aligned} \tag{B.5}$$

It can be seen right away that Equations (B.3) and (B.4) sum up to zero; the expression for the optimal tax rate is hence given only by:

$$-\zeta_p \sum_m \frac{\partial a_{p,m}}{\partial \tau_p} \tau_p = \left(\sum_{i,j} w_{i,j} (MUA)_{i,j} \sum_m \frac{\partial a_{p,m}}{\partial \tau_p} + \sum_j (e_{p,j} - a_{p,j}) \sum_m \Psi_{p,m} \frac{\partial F_{p,m}}{\partial L_{p,j}} \right). \tag{B.6}$$

Using Equation (B.5), this expression can be simplified further to

$$-\zeta_p \sum_m \frac{\partial a_{p,m}}{\partial \tau_p} \tau_p = \left(\sum_{i,j} w_{i,j} (MUA)_{i,j} \sum_m \frac{\partial a_{p,m}}{\partial \tau_p} + \sum_{i,j \neq m_i} \Psi_{i,j} \left(\Omega_{i,j} MVCA_{i,j} \right) \right).$$

$\Psi_{i,j}$ can be replaced by means of Equation (B.1). The expression obtained for τ_p is then equivalent to Equation (30).