Different taxes or redistribution: How to shape a just global climate policy?

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Abstract

This paper compares the effects of differentiated carbon taxes with those of a global harmonized tax associated with revenue recycling. Using a global Integrated Assessment Model representing national economies, we find that a uniform global carbon tax with lump-sum per capita recycling is the most welfare enhancing and inequality reducing policy. It can bring a welfare improvement equivalent to several percents of average global consumption until 2050. This scheme however implies large international transfers between countries. A more modest scheme, where 5% of global carbon revenues are targeted to compensate loss and damage in poor countries particularly vulnerable to the impacts of climate change, can result in strong inequality reductions, and significant welfare increases for low income countries. Differentiated taxes with country-level redistribution can have positive effects, especially on inequality, but those mainly happen after 2050, when poorer countries have larger carbon tax revenues to redistribute.

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1 Introduction

Climate change is one of the most pressing issues that societies have been facing for decades. However, research on climate policy often highlights the trade-off between taking action to address climate change and ensuring fairness. Indeed, evidence suggests that the burden of climate mitigation disproportionately falls on the poor (Ohlendorf et al., 2021). Additionally, poorer nations are less able to afford mitigation and adaptation policies (Dellink et al., 2009). In addition, the effects of climate change are not equally distributed, and vulnerable countries and households are disproportionately affected. This has led to growing concerns about climate justice, because those who suffer more from climate change are not necessarily those who contribute more to greenhouse gas emissions. These concerns have hindered the political acceptability of climate policy.

The equitableness of climate policy can be related to its design. One of the key mechanisms for addressing climate change is the implementation of a carbon tax. The tax is used to internalize the cost of carbon emissions, making polluters pay for the damages they cause. However, carbon taxes can have differential impacts on different groups and countries, depending on their income level, geographic location, and reliance on fossil fuels. This suggests that perhaps different groups should be taxed differently. Also, many policy proposals neglect the possibility of using the revenues from a carbon tax to address fairness concerns. Revenue recycling has been extensively studied, and the option of equal per capita refunds has been identified as a viable solution. Evidence suggests that recycling carbon tax revenues in a progressive way within a country can benefit most citizens immediately, and foster political acceptance (Klenert et al., 2018; Carattini et al., 2019). Global recycling also has potential to garner public support (Dechezleprêtre et al., 2022), and can address concerns about inequality and poverty (Soergel et al., 2021; Budolfson et al., 2021; Davies et al., 2014).

Global recycling of (part of) the carbon tax could entail transfers between different countries. Although it is sometimes considered difficult to implement such transfers, the idea that more developed countries should help developing ones to ensure their transition and adaptation to climate change is widely accepted in international negotiations. For instance, the Paris Agreement envisions financial transfers in the form of assistance (Paris Agreement, Article 9 UNFCCC, 2015):

> "1 - Developed country Parties shall provide financial resources to assist developing country Parties with respect to both mitigation and adaptation in continuation of their existing obligations under the Convention.
> 2 - Other Parties are encouraged to provide or continue to provide such support voluntarily."

More generally, the recent debates about funding the "Loss and Damage" faced by developing countries have renewed the concerns that some transfers from developed countries could be necessary to create a Loss and Damage fund. It is not completely settled how such a fund should be financed. Many of the financing mechanism to address Loss and Damage in developing countries listed in the Warsaw International Mechanism rely on voluntary contributions to subsidized risk management frameworks (e.g. catastrophe risk insurance, or catastrophe bonds). However, those approaches may become more expensive with increasing climate damages, and are not adequate to face slow-onset events or non-economic Loss and Damage (Gewirtzman et al., 2018). Robinson et al. (2021) argue that levies and taxes should instead be used, because they are seen as relatively fair, predictable, adequate, transparent, and additional. A global carbon tax on some types of emissions – for instance emissions from air travel and ship fuels that are not currently taxed – is a prominent solution being discussed (Roberts et al., 2017). Emissions from air travel and ship fuels amount to about 5% of total CO2 emissions from human activities and could thus represent about 5% of the carbon tax if the tax is levied on all emissions.

In this paper, we study the effects of carbon taxation and its redistribution on consumption, inequality and welfare. To do so, we use an Integrated Assessment Model (IAM) in the spirit of Nordhaus (2017), which is built on the NICE model (Dennig et al., 2015; Budolfson et al., 2021). Our new version includes distribution, damages and mitigation at the country level – allowing to better assess the difference between country-level policies and more global policies that allow transfers between countries. We compare the effects of different policy designs for a transition meeting a 2°C temperature increase target: optimally differentiated taxes versus a global carbon tax; and in the case of the global carbon tax, different redistribution schemes – at the country level, at the global level, or somewhere in-between to reflect a loss and damage policy. The comparison is based on average consumption, on an inequality index (the Gini index), and on a more comprehensive welfare measure based on Atkinson (1970). To the best of our knowledge, our paper is the first to compare the effects of differentiated taxes with those of a global harmonized tax associated with recycling of the carbon tax revenue in an Integrated Assessment Model that includes within country distributions of income.

We find that uniform global carbon taxation with global per capita recycling would decrease global inequality and improve global welfare the most – with a gain equivalent to several percents of average global consumption until 2050 compared to the scenario without climate policy. However, governments might be reluctant to participate in revenue sharing at such a scale. If intergovernmental transfers are limited, our results show that differentiated taxes with domestic recycling of the revenues have the strongest impact on global inequality; while the most welfare gains can be achieved through uniform global taxation with 5% of revenues targeted to poor countries experiencing Loss and Damage and 95% of revenues recycled domestically.[1] The recycling option with 5% of global revenues targeted to Loss and Damage can result in strong inequality reduction, and significant welfare increases for low income countries particularly vulnerable to the impacts of climate change, while leaving middle and high income countries with resources to recycle domestically. In addition, we find that the gains from differentiated or global taxes with domestic recycling of revenues differ in terms of timing: a uniform tax yields larger benefits around 2040 in most countries, but differentiated taxes yield larger benefits earlier for rich countries and later for middle income countries.

2 Literature

It is often said that optimal global climate policy requires a worldwide single carbon tax. Chichilnisky and Heal (1994) have however shown that this is only the case if distributional issues are ignored, or if transfers are made between countries. Otherwise, a policy in which different regions face different carbon prices may be superior to one with a single global carbon price. Sandmo (2006) investigated the general question of optimal Pigouvian taxes

[1]The 5% of revenues correspond to the 5% of emissions related to air travel and international shipping. Lee et al. (2021) compute that global aviation operations contribute to 3.5% of the net anthropogenic effective radiative forcing. Traut et al. (2018) mention that CO2 emissions from international shipping represent about 2.2% of the global total CO2 emissions.

for a global externality in a static framework. Similarly to Chichilnisky and Heal (1994), when lump-sum transfers are not possible, he found that optimal Pigouvian taxes on the externality should not be equalized across countries, but rather that poor countries should impose lower taxes than rich countries. D'Autume et al. (2016) show that the results carry over in a second-best setting in which governments have to resort to distortionary taxation to finance the public good. Recently, Fleurbaey and Kornek (2021) have shown in a general framework that the single price result holds only when income taxation transfers are possible, but that otherwise personalized prices for an externality can enhance social welfare if they are redistributive.

Hourcade and Gilotte (2000) show that several factors of heterogeneity between countries make a uniform global carbon tax non optimal (in particular, utility from energy services, uneven access to the best available technologies, and country-specific side effects of a tax). Similarly, Bataille et al. (2018) argue that, with country-specific development objectives and constraints, multiple market failures and limited international transfers, carbon prices do not need to be uniform across countries.

Most of those results are in theoretical models, or in static frameworks. Very few papers have studied differentiated carbon prices (or carbon taxes) in IAMs. Tol (2001) and Tol (2002) have looked at differentiated emission abatement rates for different regions based on several approaches to global justice. Reviewing the literature, Engström and Gars (2015) argue that in IAMs in the vein of Nordhaus and Yang 1996's RICE model, near zero lump-sum transfers and a uniform tax rate are optimal by assumption, due to the use Negishi weights. Of course, Negishi weights have been criticized precisely because they tend to cancel any concerns about inequalities between world regions. Anthoff (2009) calculates optimal differential prices using the FUND IAM without such Negishi weights. He finds that optimal mitigation is less stringent when using differentiated prices. Budolfson and Dennig (2020) perform the same exercise in the multi-region IAM NICE. They find that this entails significant welfare gains over the single price case.

The papers studying differentiating carbon prices typically do not take into account that the proceeds of a carbon tax can be redistributed at the country level or globally. However, many studies provide evidence that recycling a carbon tax can reduce inequality, limit poverty, and improve welfare. This has been shown with Computable General Equilibrium (CGE) models for several countries (see Felder and van Nieuwkoop, 1996, for Switzerland; Fragkos et al., 2021, for the European Union Member States; Beck et al., 2016, for Canada; Garaffa et al., 2021, for Brazil; Rausch et al., 2011, for the USA) and also from input-output models with surveys (see Vogt-Schilb et al., 2019, for sixteen countries of Latin America and the Caribbean). Using a CGE model of the Chinese economy, Liang and Wei (2012) have also shown that lump-sum transfers are the only revenue recycling scheme that can fully prevent the widening of income gap between rural and urban households due to the carbon tax. Similarly, Young-Brun (2023) provides evidence that recycling revenues from a carbon tax can limit the differential impacts for rural and urban households in some European countries. Some papers have also used microsimulation models to assess the distributional effects of carbon pricing with and without redistribution, and highlighted that lump-sum taxes can benefit the poorest households (see Williams et al., 2015, for the USA; Berry, 2019, and Ravigné et al., 2022, for France; Callan et al., 2009, for Ireland; Steckel et al., 2021, for several countries in Asia). More generally, in a review of the empirical literature, Köppl and Schratzenstaller (2022) gather evidence that lump-sum transfers are better suited to mitigate the regressive effects of carbon taxes on lower income groups than a reduction of labour taxes. This suggests that we should focus on lump-sum transfers as a recycling scheme, which is what we do in the present paper.

The papers above focus on the distributive and welfare effects of redistributing carbon tax revenues within a country. Feindt et al. (2021) use a micro-simulation model to examine how a European carbon price will affect households in twenty-three countries of the European Union, and compare within country vs. European-wide redistribution. They show that national lump-sum redistribution can yield a progressive incidence, but that European-wide redistribution is more effective for the most affected households. Beyond the regional level, some papers have investigated the ability of a global carbon tax to improve access to infrastructures or to reduce inequality and poverty. Jakob et al. (2016) assess the potential of using revenues from global uniform carbon taxation to finance investment in infrastructure. They focus on a global carbon price pathway for a 2°C scenario and find that recycling revenues at the country-level could be sufficient to finance universal access to most types of infrastructure, except in Sub-Saharan African countries, but that global redistribution schemes are necessary to finance such universal access in all countries. Using the integrated assessment model AIM, Fujimori et al. (2020) compare the revenues raised by a global carbon tax to the income gap relative to the absolute poverty line in 1.5 and 2°C climate scenarios. They argue that a share of carbon tax revenues from high-income countries could be used to help eradicate poverty in low-income countries. Soergel et al. (2021) assess the impact of a sustainable development pathway that combines climate policy with other policy interventions, including a climate and development scheme (international redistribution of part of carbon tax revenues, and within region equal per capita redistribution of the carbon tax revenues). They show that the sustainable development pathway can achieve a large reduction in inequality within regions, measured by the fraction of the population in relative poverty (below 50% of the national median income). Such a pathway can also significantly reduce extreme (absolute) poverty, although poverty does not completely disappear by 2030.

The paper closest to ours on the question of redistributing carbon tax revenues is Budolfson et al. (2021), which also uses the NICE model to study the distributive impact of climate policy. They focus on the case of a uniform global carbon tax where redistribution is made on an equal per capita basis within each of the original twelve regions of the RICE model. They show that equal per capita global redistribution of carbon tax revenues may yield positive welfare effects, at least in poorer regions and at the global level. We depart from their work by having redistribution at the country (rather than region) level, combined in two of our scenarios with some international transfers towards the poorest countries. To achieve this improved granularity, we develop a version of NICE with 179 countries. To the best of our knowledge, only the RICE50+ model by Gazzotti (2022) achieves a similar degree of granularity in an IAM including income heterogeneity within a region. However, they do not include within-country inequality and do not have country-level modelling for many Sub-Saharan African countries that are likely benefiting the most from a global redistribution.

One of the main contribution of our paper is to bridge the gap between the approaches proposing differentiating the carbon tax and those studying the potential benefits of international transfers and redistribution in the case of a uniform carbon tax. We ask the following questions. Assume that we cannot achieve international transfers, how much welfare gains can differentiated carbon taxes still bring? Assume on the contrary that we need a uniform carbon tax (for efficiency reasons, or to avoid carbon leakage), how much welfare gains can stem from implementing appropriate transfers? Those question are similar to those raised by Bauer et al. (2020). They use the ReMIND-MAgPIE integrated assessment model to study the efficiency-sovereignty[2] trade-off of using uniform versus differentiated carbon tax in a 2°C scenario. Their objective is different from ours in that they focus on implementing an "equitable effort sharing" rule across the twelve ReMIND regions, rather than maximizing welfare or reducing inequality. In addition, they do not represent income heterogeneity within regions, thus loosing some of the benefits of redistribution for within country inequality. And they also work at the more aggregate twelve regions levels, not the country level.

3 Methods: A global integrated assessment model with inequality within countries

We update the Nested Inequalities Climate Economy model (NICE), a global climate policy model that features within-region inequality for the twelve regions of the RICE2010 model (Dennig et al., 2015) with sub-regional consumption quintiles. We build on the latest version of the model, which allowed for carbon tax revenue recycling (Budolfson et al., 2021). We modify the model to investigate carbon tax and revenue recycling scenarios at the country and global levels. To do so, we augment the granularity of the model, and disaggregate the twelve original regions into 179 countries[3].

3.1 Within country inequality and distributional impacts

While the previous versions of the NICE model featured consumption quintiles (Dennig et al., 2015; Budolfson et al., 2021), we here introduce consumption deciles. We calibrate baseline deciles using country income gini projections until 2100 in the SSP2 scenario, as provided by Rao et al. (2018). We assume that for each country i, income is distributed across deciles according to a lognormal distribution $LN(\mu_i, \sigma_i)$. We can deduce standard deviations σ_i from country Gini indices.[4] From the standard deviations σ_i, we can deduce a Lorenz curve for each country and each time step, from which we obtain country income deciles over time. We use a transformation vector to derive consumption deciles from income deciles, following the approach proposed by Pinkovskiy and Sala-i Martin (2009).

Climate damages, mitigation costs and carbon tax burdens are distributed across deciles using consumption elasticities (see Dennig et al., 2015, for the use of elasticities in the modelling of distributional impacts in NICE). The initial burden of a carbon tax is the distribution of mitigation costs and carbon tax payments before tax revenues are recycled

[2] Sovereignty referring to the "nation states' aim to maintain governing control of economic resources by limiting international transfer payments".

[3] This set of countries corresponds to the set represented in the Shared Socioeconomic Pathways, with Somalia, Venezuela, New Caledonia and Trinidad and Tobago removed due to data limitations.

[4] Cowell (2011) indeed show that, in the case of a lognormal distribution, we have the following relation:

$$\sigma_i = \sqrt{2} \cdot \Phi^{-1}\left(\frac{Gini_i + 1}{2}\right),$$

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

and redistributed. Within each country, mitigation costs and carbon tax payments are assumed to be distributed across deciles using the same consumption elasticity of the initial burden for a given country at a given time. Consumption elasticity of the initial burden is calibrated using the estimation provided in Budolfson et al. (2021), which they derive from a review of the literature on the initial burden of carbon taxation across countries before the redistribution of tax revenues. The consumption elasticity of the initial burden $w_{i,t}$ of country i at time t is thus given by: $w_{i,t} = \hat{\alpha} + \hat{\beta} \cdot \log y_{i,t}$, with y the GDP per capita. Parameters $\hat{\alpha}$ and $\hat{\beta}$ are set at 3.22 and -0.22, respectively. This elasticity is thus endogenous, as it depends on GDP per capita computed by the model at each time step.

The distribution of climate damages across deciles could range from being inversely proportional to consumption (damage elasticity of consumption $\xi = -1$), to being proportional to consumption ($\xi = 1$) or more than proportional to consumption ($\xi > 1$). The literature does not yet provide empirical estimates available across countries on the differentiated impact of climate damages across income or consumption quantiles. In absolute value, the richest will suffer more from climate change than the poorest, simply because they have more to lose. Therefore, we can assume that the distribution of damages across deciles will not be flat, i.e., $\xi > 0$. We assume that damages are likely to be less than proportional to income or consumption, i.e., $\xi < 1$. We set the consumption elasticity of damages at 0.9.

3.2 Country level emissions and abatement

Country level emissions intensities of output are computed until 2100 from projected GDP streams based on the SSP2 trajectory, and from emission trajectories based on the ReMIND model in a business-as-usual scenario.

Next, we model country level mitigation trajectories. We use the same abatement cost function as in Barrage and Nordhaus (2023), but differentiate the multiplicative parameter by country. As a result, the cost of abatement as a share of gross output in country i for a mitigation rate of μ_i is

$$\Lambda_{it} = \theta_{1,it}\mu_{it}^{\theta_2},$$

with $\theta_2 = 2.6$. We calibrate the multiplicative parameter $\theta_{1,it}$ using the global backstop price from Barrage and Nordhaus (2023) and the assumption that the marginal cost of abatement at a 100% mitigation rate per unit of emission (in USD per unit of emissions) is equal to the global backstop price in every country. Details can be found in Appendix A.1. As a result, a global and uniform carbon tax leads to the same abatement rate trajectory in every country, but to heterogeneous abatement costs in terms of share of gross output. Finally, we rule out negative emissions by setting the maximum mitigation rate to 100%.

3.3 Country level climate damages

The global temperature change caused by greenhouse gas emissions is modeled using mimiFaIRv2 (Errickson et al., 2022), a Julia implementation of the Finite Amplitude Impulse Response model (FaIR). FaIR is a climate model designed to reproduce the global climate system's response to greenhouse gas emissions with good accuracy, and to capture non-linearities in the carbon cycle, while keeping complexity level and run-time low (Leach et al., 2021). The global temperature anomaly is downscaled to a country level temperature anomaly with pattern scale coefficients taken from the Coupled Model Intercomparison Project Phase 6 (CMIP6, O'Neill et al., 2016).

Following the usual practice in the literature, we assume that climate damages as a share of GDP are a function of the temperature anomaly. But contrary to most existing approaches (in particular models derived from the RICE model by Nordhaus and Yang, 1996), the country damage function depends on the local temperature anomaly that we obtain through our downscaling methodology. More specifically, the country-level damage function has the generic form:

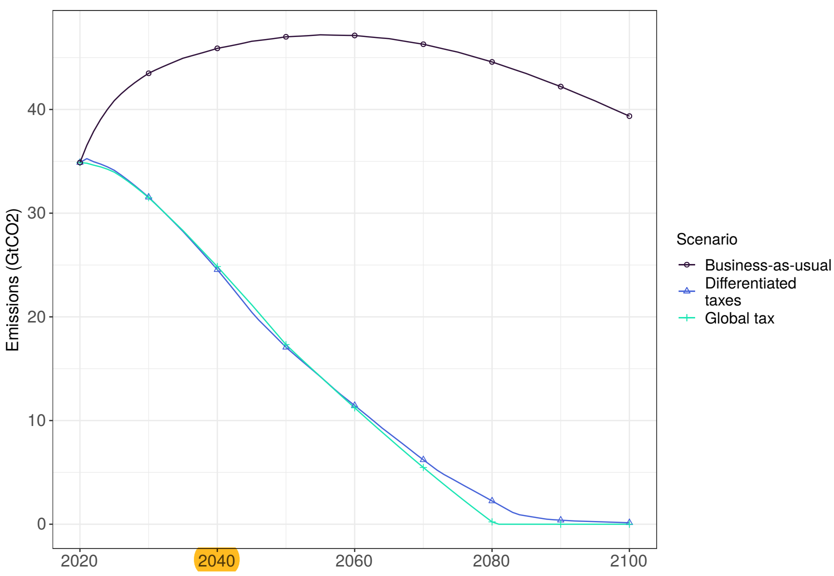
$$\delta_i(\Delta_i T) = \beta_{i1} \cdot \Delta_i T + \beta_{i2} \cdot (\Delta_i T)^2,$$

where $\Delta_i T$ is the local temperature anomaly and $\delta_i(\Delta_i T)$ is the damage loss measured as a share of GDP lost for a given temperature anomaly. Parameters β_{i1} and β_{i2} are country-specific parameters that are calibrated to represent a general relationship between temperature increase and climate damages, as predicted in the econometric analysis by Kalkuhl and Wenz (2020). More details can be found in Appendix A.2.

3.4 Globally uniform and differentiated carbon taxes by country

We implement 2°C scenarios with either a global uniform tax or differentiated taxes by country. For the global uniform tax, we find a carbon tax trajectory that abides to that constraint and that is linearly increasing with time. For the differentiated tax by country, we use a rule derived from maximisation of the sum of country utilities under an emission budget constraint. The rule expresses the ratio of carbon taxes in a country relative to the reference as a function of the savings rate and marginal utility of the country and the reference. We choose the United States as the reference, and find the linear tax trajectory that best approximates the global carbon tax trajectory in terms of emissions before 2050. The detailed method is presented in Appendix A.3.

Figure 1: CO_2 emissions ($GtCO_2$) for the business-as-usual scenario SSP2 (black), and for the 2°C scenarios implemented via a global uniform tax (blue green) and via differentiated taxes across countries (dark blue).



The resulting emissions are presented in Figure 1: the 2°C emission trajectories are very close, and total carbon budgets over the 2020-2100 period differ only by 16 $GtCO_2$ (1.4% of the total carbon budget compatible with limiting global temperature increase to 2°C). Figure A.1 in the Appendix presents a few examples of implemented tax trajectories in the differentiated tax alternative of the 2°C scenario (dark blue) for countries on all continents and with various income levels (Guinea, India, China, Indonesia, Brazil, Dominican Republic, Republic of Korea, Germany and the USA), and the global uniform carbon tax (blue-green). By construction, the global uniform carbon tax is always lower than the differentiated taxes in high income countries (e.g., USA, Germany and the Republic of Korea).

3.5 Alternative revenue recycling options

Our two carbon tax scenarios compatible with 2°C result in aggregate revenues up to 4 trillion dollars (up to 1.5% of global GDP) for the uniform global tax, and up to 3 trillion dollars (up to 1.25% of global GDP) for the differentiated taxes (Figure A.8). We consider six alternatives regarding the distribution of carbon tax revenues.

In the case of differentiated taxes by country, we explore two options: one where the recycling of revenues is neutral, i.e., carbon tax revenues are refunded within each country according to the initial income distribution; the other where carbon tax revenues are redistributed as equal per capita payments within countries.

In the case of a global uniform carbon tax, we consider four alternatives. The first two options mirror the previously described scenarios for differentiated taxes: the first one assumes a redistribution of the revenues of the global carbon tax which does not change the initial distribution, the second assumes that the revenues of the global tax are redistributed on an equal per capita basis within each country.

Two additional alternatives are considered. The first one assumes that all tax revenues are collected globally and redistributed equally per capita at the global level. This scheme thus induces international transfers between countries, i.e., revenues raised in a given country are not necessarily redistributed within that country.

The last option seeks to represent a possible Loss and Damage policy. It assumes that a given share of the revenues are redistributed to low and low-middle income countries[5] only, and proportionally to the value of a risk index derived from the INFORM Index for Risk Management (Marin-Ferrer et al., 2017).[6] Denoting J the set of low and low-middle income countries, the share of country $i \in J$ in the global Loss and Damage transfers π_t^{LD} writes

$$\frac{\pi_{it}^{LD}}{\pi_t^{LD}} = \frac{\iota_i N_{it}}{\sum_{j \in J} \iota_j N_{jt}} \tag{3.5.1}$$

with ι_i the risk index of country i and N_{it} the population of country i in period t.

We set the share of revenues allocated to Loss and Damage transfers at 5% of global carbon tax revenues. As explained in the introduction, this option can be seen as imposing a global carbon tax, but only taxation related to air travel and ship fuels is used to finance a Loss and Damage fund that is directed towards poorer countries. With our assumption, the rule for allocating resources to countries is based on their vulnerability to climate risk assessed by our Risk Index. This can be thought of as an implementation of the Loss and Damage fund currently discussed. In that scenario, the remaining carbon tax revenues

[5] World Bank classification, see Appendix A.5 for the list.

[6] See Appendix A.6 for a description of our modification of the INFORM Risk Index.

are redistributed within countries on an equal per capita basis. In Section 4.4, we discuss other possible implementations based on the damages faced by the poorest countries.

The results section below describes the consequences of these policy alternatives.

4 Results

4.1 Global results

Introducing a global carbon tax or differentiated carbon taxes at the country level implies very different burden sharing of emission reductions. The burden sharing in the differentiated tax case is only based on fairness considerations – not efficiency considerations. On the contrary, a global carbon tax equalizes the marginal cost of abatement in all countries, which is more cost-effective for a given level of global emission reduction.

So, unsurprisingly, we find that differentiating carbon taxes implies higher total abatement costs at the global level. Figure 2 indeed represents the percent change in average per capita consumption at the global level compared to business-as-usual (BAU) in the two tax scenarios.

Figure 2: Difference in consumption per capita in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives. Note that all global tax curves coincide (red line), and both differentiated tax curves coincide (blue line).

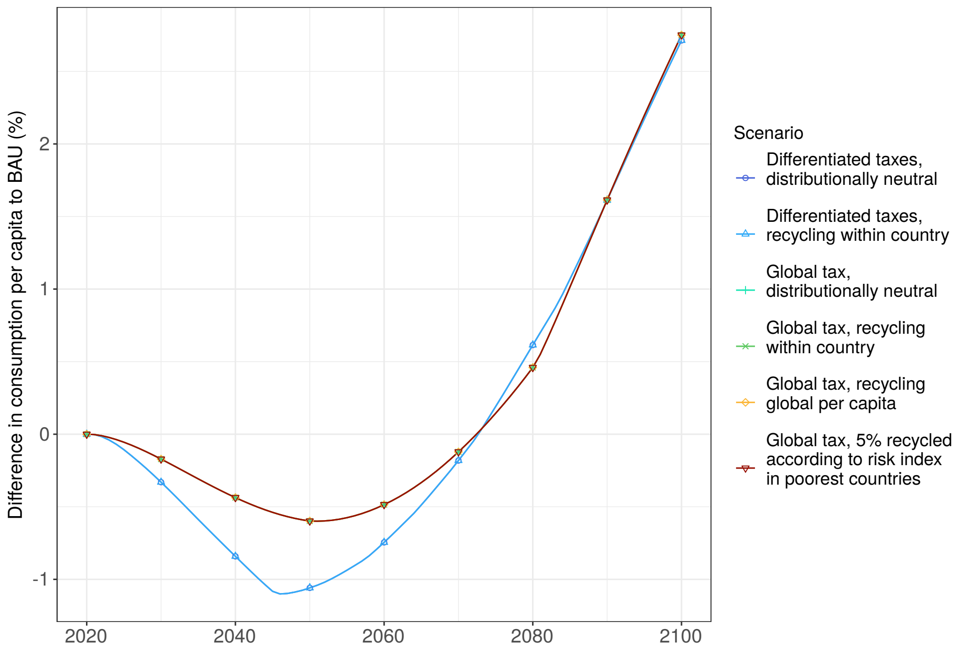
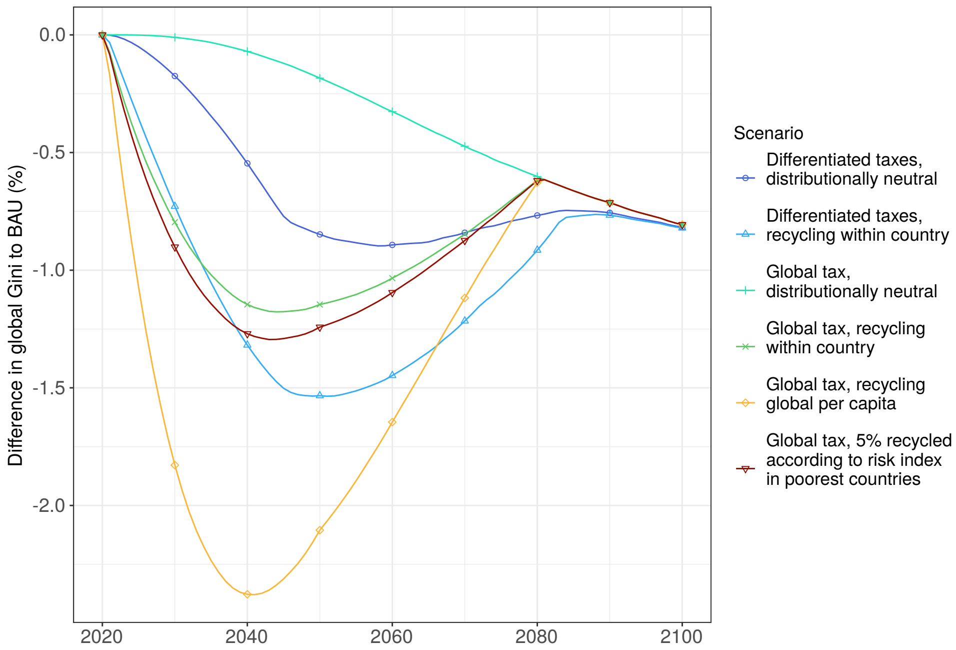


Figure 3 shows contrasted results in terms of global inequality measured by the global consumption Gini. The global consumption Gini is calculated using per capita consumption of all deciles in all countries, weighted by the population of each decile. The results show that global inequalities are reduced in all 2°C scenarios compared to the business-as-usual, including in both cases where tax revenues do not alter the distribution (blue-green and dark blue). This is because damages are assumed to be distributed disproportionally to consumption across deciles (the consumption elasticity of damages is set to 0.9), and those damages are partly avoided in the 2°C scenario. In addition, the mitigation costs are progressive is some poorer countries in the shorter run.

As argued before, differentiated taxes can, in the absence of redistribution, improve fairness and equity. Comparing the cases with distributionally neutral recycling, differentiated taxes (dark blue) result in a larger reduction in the global Gini than a uniform global tax (blue-green). In the absence of international transfers and within country lump-sum recycling, differentiated taxation indeed improves global equity with respect to uniform taxation.

Figure 3: Difference in the global consumption Gini index in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives.

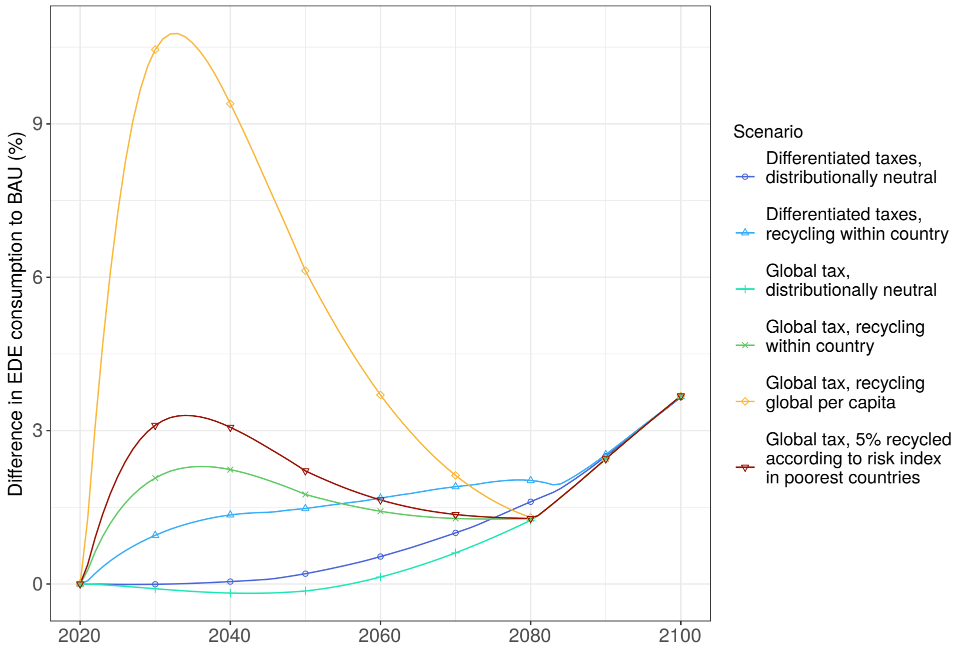


Next, all redistribution schemes reduce inequalities compared to a neutral redistribution, until carbon tax revenues fall to zero (in 2080 in the case of a global carbon tax, in 2100 in the case of differentiated taxes). The policy alternative that reduces global inequalities the most is the global uniform tax with equal per capita revenue recycling (orange). It is superior to other policy alternatives until after 2060, when carbon tax revenues start to dwindle.

Looking at the schemes with recycling within countries, uniform and differentiated carbon taxes yield approximately the same reduction in the global Gini until the middle of the 2030s. After that point, differentiated taxes with intra-country recycling (light blue) result in larger Gini reductions than a global tax with intra-country recycling (green). The "Loss and damage" scenario (red), where 5% of a global carbon tax revenues are recycled to the poorest countries according to a climate risk index, gives slightly superior but similar results in terms of consumption Gini as a global tax with recycling within countries (green).

The equally distributed equivalent (EDE) consumption is the level of consumption that, if given to each member of a given population, yields the same level of welfare as the actual distribution of consumption. Its calculation is described in Appendix A.7. This

Figure 4: Difference in the equally distributed equivalent (EDE) consumption in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives.



is a measure of welfare, and can be used to rank policy alternatives. Our results show that a global uniform tax with equal per capita redistribution of carbon tax revenues is superior to all other policy alternatives according to that metric (Figure 4). This result mirrors the global consumption Gini presented above. The rest of the hierarchy of policies that prevailed in terms of global consumption Ginis is not fully preserved here, as the global tax with a "Loss and Damage" fund (red) is superior to the differentiated taxes with recycling within countries (light blue) in terms of equally distributed equivalent consumption gains until 2060. This is because welfare gains combine gains (and losses) of average consumption on the one hand, and inequality reduction on the other hand (see Appendix A.7). The differentiated tax case induces efficiency loss (i.e., larger losses in terms of average consumption) compared to a global carbon tax. The gain of equally distributed equivalent consumption in 2°C scenarios compared to the BAU also depends on the assumed inequality aversion, here set at $\eta = 1.5$, in line with Barrage and Nordhaus (2023). Our sensitivity analysis (Appendix A.9) shows that a lower inequality aversion does not change the ranking of policies in terms of EDE consumption. As expected, the size of the overall welfare gain decreases when inequality aversion decreases in the all scenarios with redistribution.

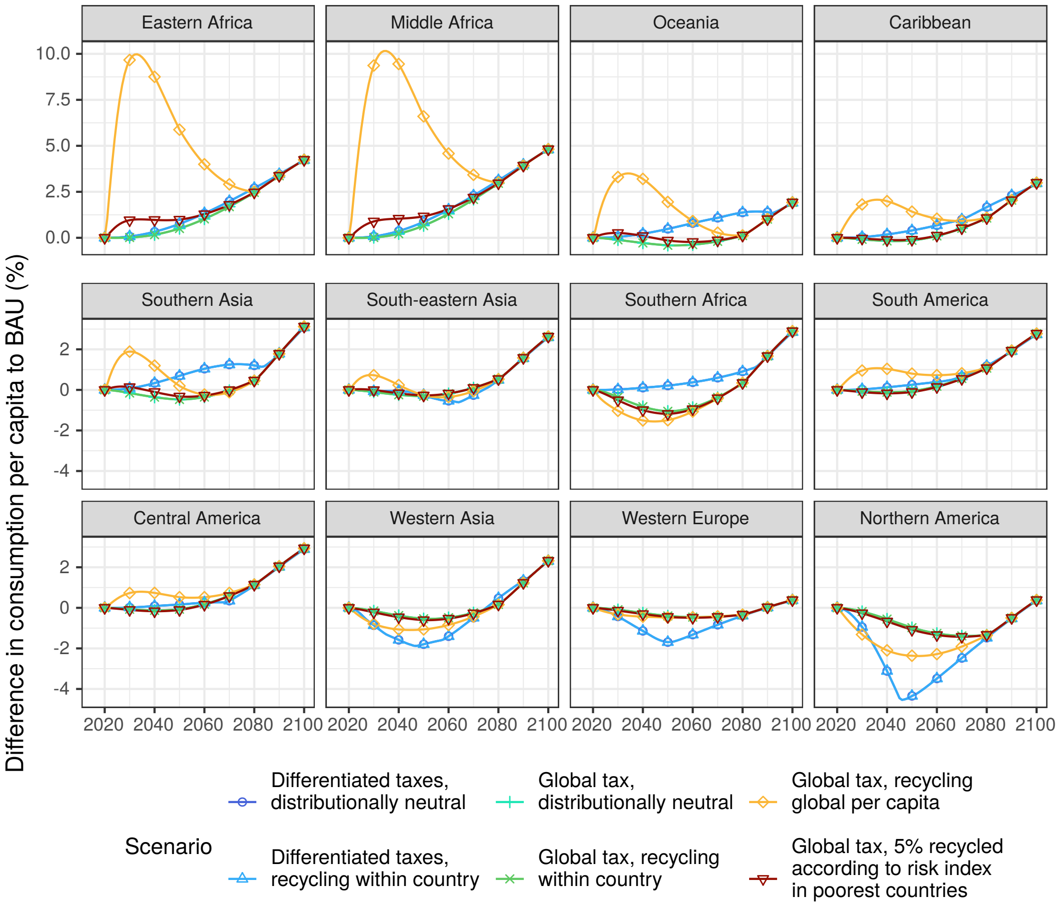
4.2 Regional results

We compute aggregates for twenty geographical regions from the World Population Prospects (UN, 2022). We display the results for twelve of those twenty regions.

While the global results show an aggregate loss in consumption per capita in the 2°C scenario compared to the business-as-usual in the short to medium term (Figure 2), regional results can give a more contrasted view, depending on the policy alternative

(Figure 5).

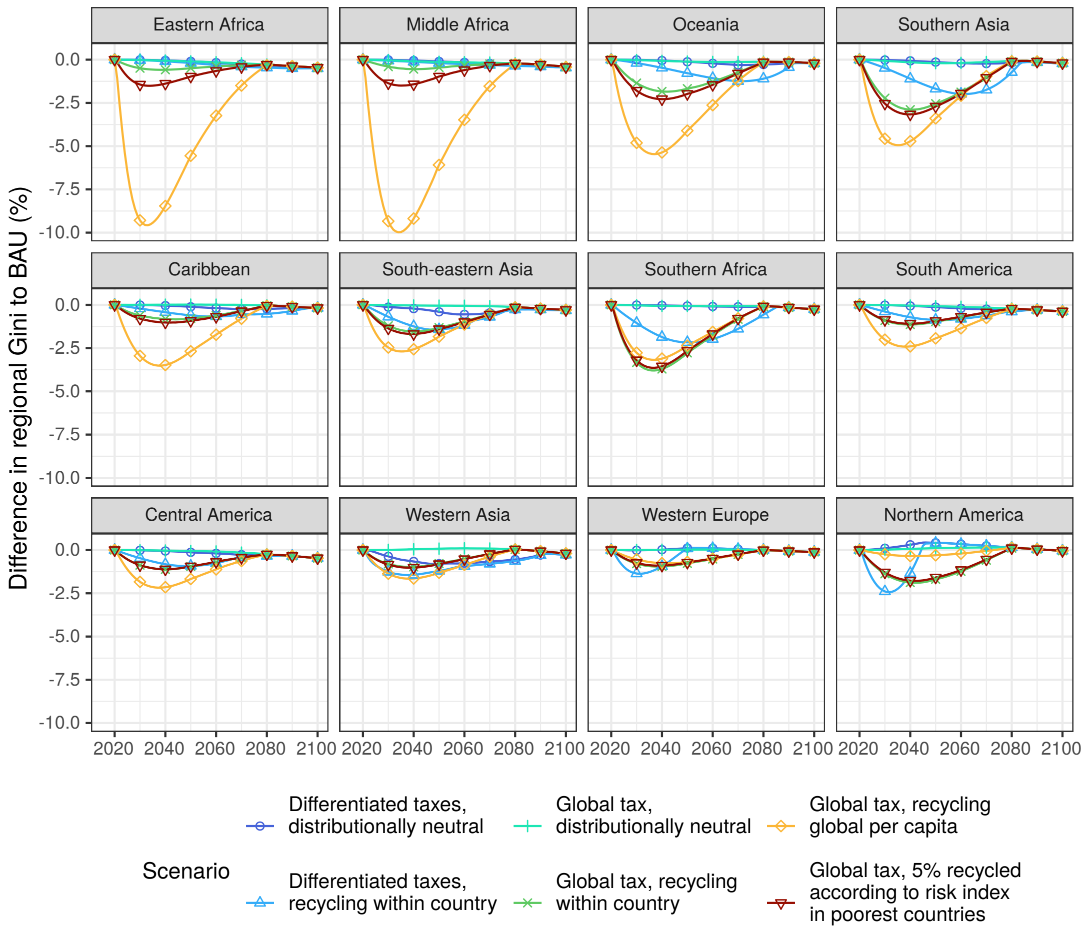
Figure 5: Difference in regional consumption per capita in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives.



In the scenarios without international transfers, differentiated taxes (dark blue and light blue) and a uniform global tax (blue-green and green) tend to increase consumption per capita in the poorest regions and decrease consumption per capita in the richest regions with respect to the BAU. This is because, in those regions, the gains from avoiding damages quickly exceed the costs of reducing emissions. For the poorest regions, such as Eastern Africa or Middle Africa, differentiated and uniform taxes result in very similar increases in consumption per capita. This is explained by large avoided climate damages and low costs from emissions reduction (because emissions are low in the short run). For middle income regions, differentiated taxes tend to raise consumption per capita by a few percents with respect to the BAU, whereas a global tax tends to slightly decrease consumption per capita. By contrast, in the richer regions, both differentiated and global taxes result in a decrease in consumption per capita before 2080, and differentiated taxes decrease consumption per capita more than a global uniform tax. These differences reflect how, in the absence of international transfers, the differentiated carbon tax shifts part of the burden of emissions abatement to richer regions.

In the case of a global uniform tax where tax revenues are recycled on an equal per capita basis (orange), high income regions (Northern America, Western Europe) experience a relative loss in consumption per capita compared to the BAU, while several lower income regions gain in the short to medium term (e.g., Eastern Africa, Middle Africa, Southern Asia, South America, the Caribbean). Those regions benefit from the global redistribution of carbon tax revenues. Finally, in the Loss and Damage scenario, which features a transfer of 5% of global revenues to the low and middle income countries in proportion to a population weighted climate risk index, most regions are very little affected, while the poorest regions gain a few percents in consumption per capita.

Figure 6: Difference in the regional consumption Gini in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives.



Next, we study the impact of the tax and recycling schemes on regional inequality. Figure 6 shows the regional Gini, computed from the consumption deciles of countries within the region. A global uniform tax with equal per capita transfers results in the strongest inequality reduction in most regions. The only exceptions are richer regions where the carbon tax revenue per capita is higher than the global average.

Comparing differentiated taxes and global uniform taxes with within-country recycling, the ranking in terms of inequality reduction is heterogeneous across regions and time. In the poorest regions such as Eastern and Middle Africa, emissions are low in the BAU, resulting in limited potential for carbon taxation to raise revenues for recycling at the domestic level. In middle income regions, uniform taxation with domestic recycling (green) brings stronger inequality reductions earlier on in the century compared to differentiated taxation with domestic recycling (light blue). The reverse occurs in richer regions such as Western Europe or Northern America, where differentiated taxes bring stronger inequality reduction early on, due to the revenues generated in the first decades by stronger mitigation policy.

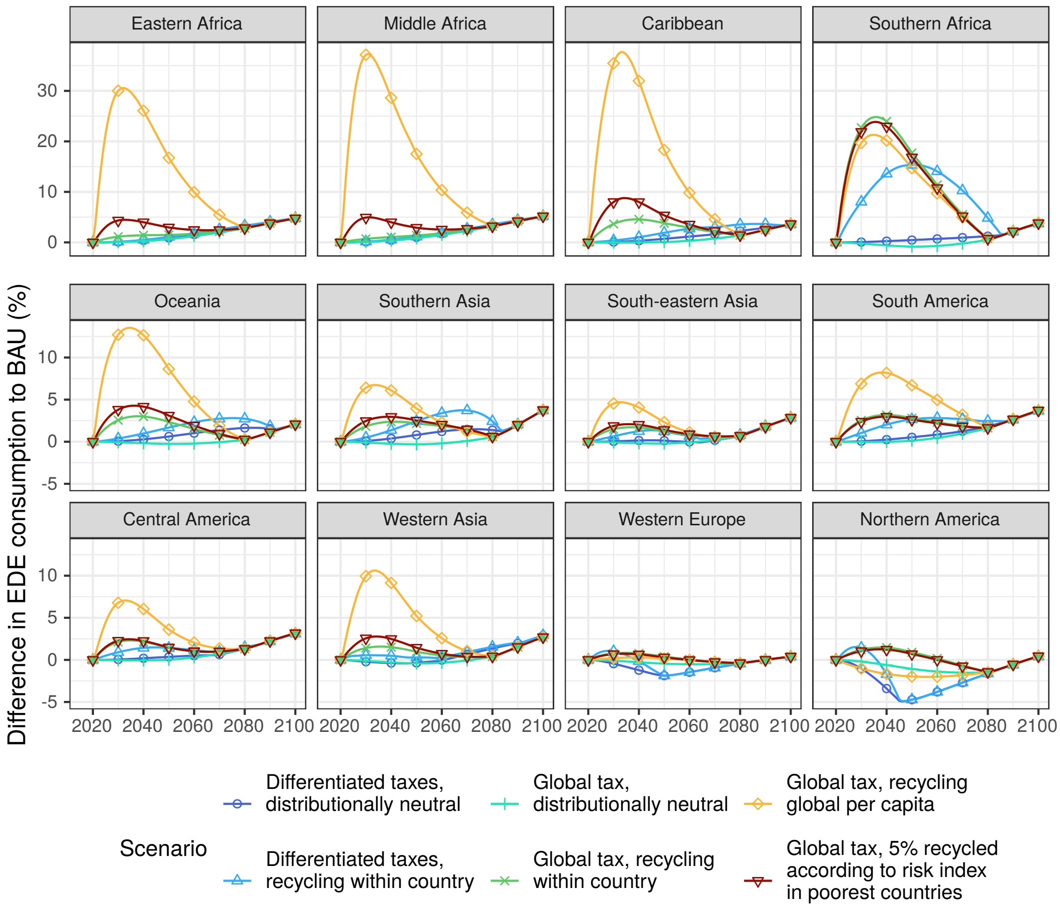
The contrast between regions is even more salient when looking at regional equally distributed equivalent consumption (Figure 7). In the scenarios without international transfers, recycling tax revenues within countries brings welfare gains with respect to the distributionally neutral scenarios. For differentiated and uniform taxes, within-country recycling increases EDE consumption with respect to the business-as-usual in middle income and rich countries, during the period before full regional decarbonization. The impact is particularly notable in regions with strong within-country inequality, such as Southern Africa. In addition, in high income regions, the differentiated tax alternative with no recycling (dark blue) brings losses in EDE consumption compared to business-as-usual of the same magnitude as the consumption per capita losses, implying that the shift in the decarbonization efforts to richer regions is not at the expense of more inequality within the richer regions.

Both scenarios with international transfers (orange and red) result in increases in EDE consumption with respect to the business-as-usual in most regions, except the richest. This is even the case for some regions where consumption per capita decreases with respect to the BAU in these scenarios, e.g., Southern Africa, which experiences losses in consumption per capita, but gains 20% in EDE consumption with respect to the BAU in the case of a global tax with global per capita recycling.

The gains in inequality-weighted welfare reflect the impact of the tax and transfers schemes on between-country and within-country inequalities. First, the global uniform tax, associated with global per capita recycling or Loss and Damage targeted recycling, results in transfers from richer and more emitting countries to poorer countries, thus reducing between-country inequality. Second, recycling tax revenues via lump-sum transfers within countries renders the policy progressive at the country level (Felder and van Nieuwkoop, 1996,; Fragkos et al., 2021; Beck et al., 2016; Garaffa et al., 2021; Rausch et al., 2011; Vogt-Schilb et al., 2019).

Global per capita recycling is the option that results in the highest increases in EDE consumption in most regions. Exceptions are richer regions such as Western Europe and Northern America or very unequal regions such as Southern Africa, for which the uniform tax with within-country recycling (green and red) performs best.

Figure 7: Difference in the equally distributed equivalent (EDE) regional consumption in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives.



4.3 National level results

In this section, we discuss the results in terms of equally distributed equivalent consumption for all policy alternatives (Figures 8 and 9).

National results mirror to some extent regional results in terms of the various impacts of 2°C policies. High-income countries experience welfare losses in scenarios with distributionally-neutral recycling or with global recycling, and even in some cases in scenarios with per capita recycling within countries (especially for differentiated taxes and in 2050, top right maps in Figures 8 and 9). On the contrary, poorer countries experience gains both in the nearer term (2030) and in the longer run (2050), whatever the scenario. But gains are larger and more widespread in the case of a global recycling per capita (bottom left maps in Figures 8 and 9).

The maps with country results highlight the very large diversity of country-level welfare impacts in scenarios with per capita recycling: the welfare impact ranges from losses larger than 5% to gains larger than 5% of welfare equivalent per capita consumption. Even within a region, individual country situations can vary substantially. For instance, in Western Asia, there are very contrasted situations in terms of average consumption level, emissions

Figure 8: Difference in the equally distributed equivalent (EDE) consumption in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives, in 2030.

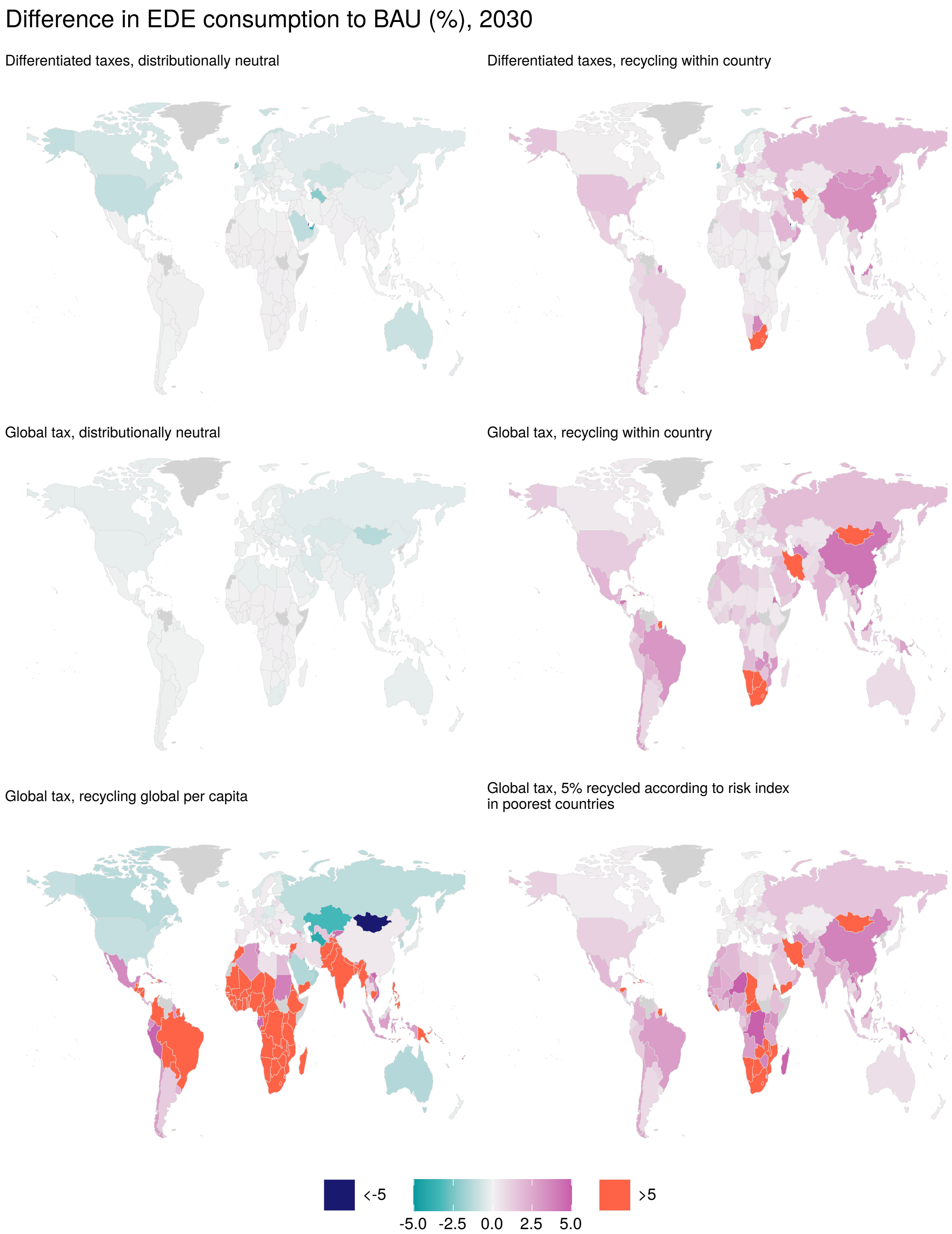
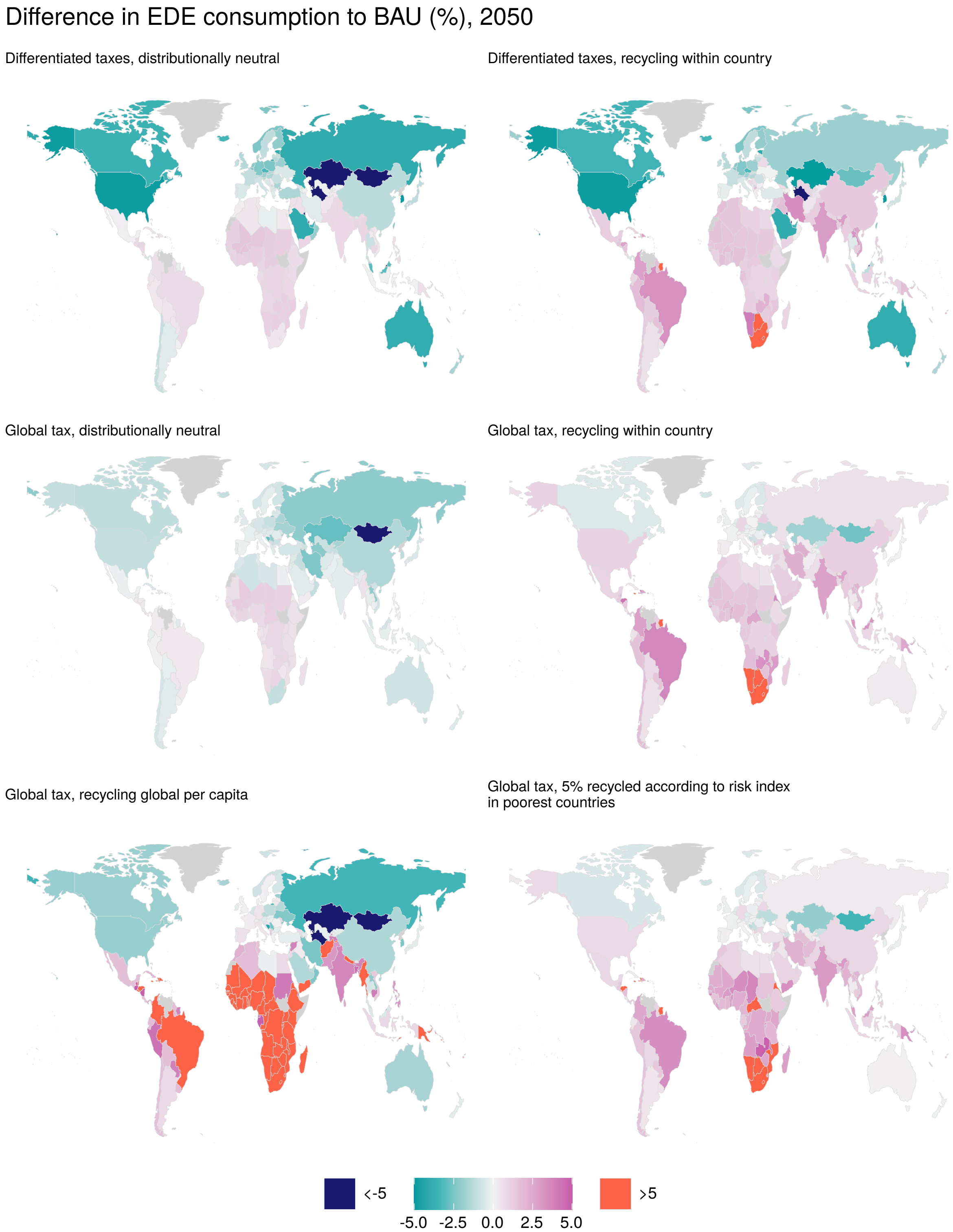


Figure 9: Difference in the equally distributed equivalent (EDE) consumption in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives, in 2050.



and inequalities, that can result in different preferred policies across countries. In 2030, the global tax with global recycling would be the worst scenario for Saudi Arabia, Oman and the United Arab Emirates, but among the best scenarios for Yemen, Syria and Jordan. Generally, the preferred policy depends on baseline inequality, the level of emissions (and cost of abatement), and the level of development.

Note also that, in the case of per capita recycling within a country, some rich countries can benefit more from the differentiated tax scheme than poorer countries. This is for instance the case of the USA in 2030, having more welfare gains than Brazil or Algeria (top right map in Figure 8). This may seem counter-intuitive as differentiated taxes are usually thought to be a better solution to mitigate transition costs in developing countries compared to a globally uniform tax when unlimited intergovernmental transfers are impossible (Chichilnisky and Heal, 1994; Hourcade and Gilotte, 2000; D'Autume et al., 2016). But this seemingly paradoxical conclusion can be explained by the fact that our scenarios include revenue recycling, which is not usually considered in other works. Recycling tax revenues can bring welfare benefits, especially in more unequal countries.

It is also noticeable that different countries face different timing for gains and losses. Some poor countries (e.g., India, but also South American countries like Bolivia), tend to gain more in the near term (2030) in the global uniform tax alternative compared to the differentiated tax setting (in the case with within country recycling). But then the differentiated tax setting can become preferable in the longer run (2050). The reverse is true for richer countries like the US.

4.4 Alternative Loss and Damage redistribution schemes

In the main results, we have used a risk index to target transfers in the Loss and Damage redistribution scheme. Using such a risk index would mean focusing on catastrophic and/or extreme climate events when compensating poorer countries. We could then neglect slow-onset events or non-economic impacts that may be very significant parts of the Loss and Damage experienced in some countries. For instance, small islands are very vulnerable to sea-level rise that may jeopardize their mere existence.

We thus test two alternative redistribution schemes that are based on modeled climate damages. Climate damages give a more comprehensive picture of the impacts poor countries will face. The first scheme uses population-weighted relative damages, i.e., damages as a share of output. Denoting J the set of low and low-middle income countries[7], the share of country $i \in J$ in the global Loss and Damage transfers π_t^{LD} writes

$$\frac{\pi_{it}^{LD}}{\pi_t^{LD}} = \frac{\delta_{it} N_{it}}{\sum_{j\in J} \delta_{jt} N_{jt}} \tag{4.4.1}$$

with δ_{it} climate damages as a share of gross output and N_{it} the population of country i in period t. The second scheme is based on absolute damages in monetary value. The share of country $i \in J$ in the global Loss and Damage transfers becomes

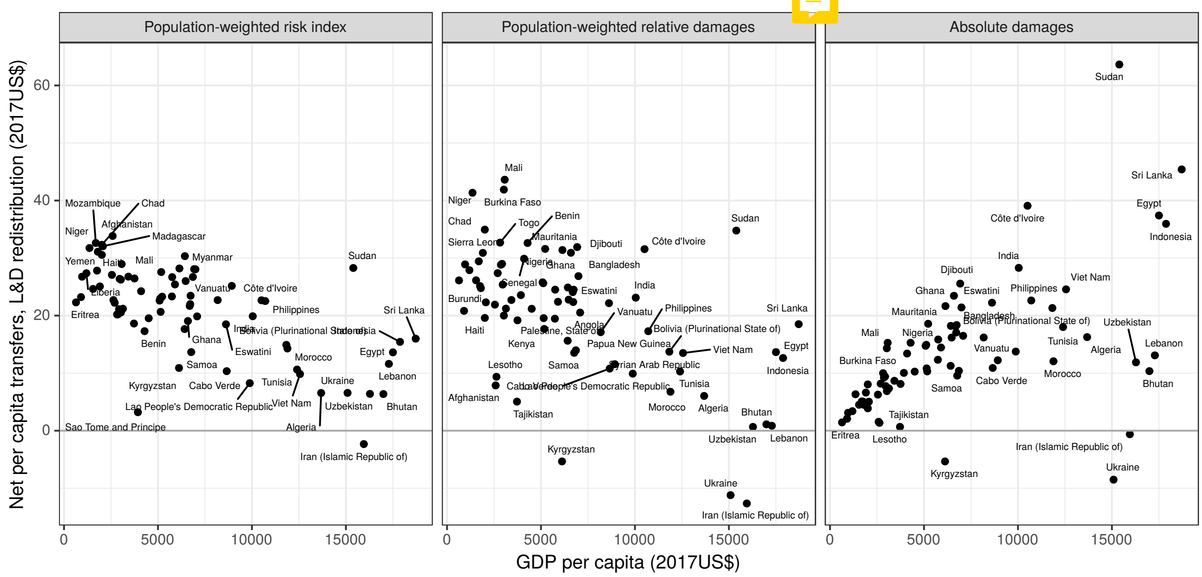
$$\frac{\pi_{it}^{LD}}{\pi_t^{LD}} = \frac{\delta_{it} Y_{it}}{\sum_{j\in J} \delta_{jt} Y_{jt}} \tag{4.4.2}$$

with $\delta_{it} Y_{it}$ absolute damages in 2017 USD.

[7]See subsection A.5 for the list.

Countries receive different net per capita transfers depending on the characteristics of the Loss and Damage redistribution scheme. In the case where the transfers are calculated in proportion to a population-weighted risk index (our baseline assumption), there is a negative correlation between the net transfers received by a country and its GDP per capita (Figure 10). This is because the risk index is negatively correlated to GDP. The maximum amount of transfers in 2030 is around 30-35 USD per capita, for instance in Niger, Mozambique, Chad, Afghanistan or Yemen. Iran is the only low-income country with a negative transfer in 2030 in that scenario. In the case of transfers proportional to population-weighted relative damages, a similar trend is found, but the maximum transfers are slightly higher (closer to 40-45 USD per capita) and directed towards different countries (Mali, Burkina Faso). In the case where net per capita transfers are proportional to absolute damages, there is a positive correlation between those and GDP per capita, as larger economies suffer larger absolute losses. These differences point to the crucial issue of redistribution design in a Loss and Damage scheme, which can significantly alter the financial situation of individual countries.

Figure 10: Net per capita transfers for three alternative Loss and Damage redistribution schemes, in 2030



5 Concluding remarks

In this paper, we analyze the impact of different types of carbon taxes and revenue recycling schemes on global inequality and welfare, using a global integrated assessment model that represents distribution, damages and mitigation at the country level.

We find that a uniform global carbon tax with global per capita recycling would be the most effective in decreasing global inequality and improving global welfare until 2050. However, governments may be hesitant to participate in revenue sharing on such a large scale. If international transfers are limited, our results suggest that good alternative policies could be to implement differentiated taxes with domestic revenue recycling, or to implement a uniform global tax with 5% of revenues targeted to poor countries experiencing loss and damages and 95% of revenues recycled domestically. The latter policy could bring strong inequality reduction and significant welfare increases for low-income countries that are particularly vulnerable to climate change impacts.

In addition, we find that the timing of the benefits from differentiated and global taxes with domestic recycling of tax revenues differs. A uniform tax yields larger benefits around 2040 in most countries, while differentiated taxes yield larger benefits earlier for rich countries, and later for middle-income countries.

Our results remain conditional on a number of assumptions, and could be extended. First, we assume that revenue can be redistributed at a negligible cost, either at the domestic or global levels. While this assumption might be a good approximation at the country level because states already operate fiscal and distributive systems, collecting and distributing funds at a global level would lead to additional bureaucratic costs. Taking those into account could reduce the magnitude of the benefits of implementing the climate policies we consider.

Next, our global and differentiated tax trajectories compatible with 2°C, as well as the sharing of mitigation efforts that they imply, depend on our assumptions about national abatement costs. To calibrate our country level abatement cost functions, we make two assumptions. First, we assume that the abatement cost functions have the same convexity. Second, we rely on the same approach as in the RICE model (Nordhaus and Yang, 1996), and assume that marginal abatement costs at 100% mitigation rate, in dollars per unit of emissions, are equal across countries. As a result, a global uniform carbon tax leads to equal mitigation rates across countries (but with heterogeneous abatement costs). Future work could explore the sensitivity of our results to these assumptions, and test alternative calibrations of the abatement costs.

Finally, our analysis could be extended to better examine the mechanisms underlying our results. In particular, we could disentangle within-country and between-country inequality effects in our global and regional results on inequality by implementing metrics such as Atkinson indices or the Theil index.

References

Anthoff, D. (2009). Optimal global dynamic carbon taxation. Working Paper WP278, ESRI.

Atkinson, A. B. (1970). On the measurement of inequality. *Journal of Economic Theory*, 2:244–263.

Barrage, L. and Nordhaus, W. D. (2023). Policies, Projections, and the Social Cost of Carbon: Results from the DICE-2023 Model. Working Paper WP31112, National Bureau of Economic Research.

Bataille, C., Guivarch, C., Hallegatte, S., Rogelj, J., and Waisman, H. (2018). Carbon prices across countries. *Nature Climate Change*, 8(8):648–650.

Bauer, N., Bertram, C., Schultes, A., Klein, D., Luderer, G., Kriegler, E., Popp, A., and Edenhofer, O. (2020). Quantification of an efficiency–sovereignty trade-off in climate policy. *Nature*, 588(7837):261–266.

Beck, M., Rivers, N., and Yonezawa, H. (2016). A rural myth? Sources and implications of the perceived unfairness of carbon taxes in rural communities. *Ecological Economics*, 124:124–134.

Berry, A. (2019). The distributional effects of a carbon tax and its impact on fuel poverty: A microsimulation study in the French context. *Energy Policy*, 124:81–94.

Budolfson, M. and Dennig, F. (2020). Optimal global climate policy and regional carbon prices. In Chichilnisky, G. and Rezai, A., editors, *Handbook on the Economics of Climate Change*. Edward Elgar.

Budolfson, M., Dennig, F., Errickson, F., Feindt, S., Ferranna, M., Fleurbaey, M., Klenert, D., Kornek, U., Kuruc, K., Méjean, A., Peng, W., Scovronick, N., Spears, D., Wagner, F., and Zuber, S. (2021). Climate action with revenue recycling has benefits for poverty, inequality and well-being. *Nature Climate Change*, 11(12):1111–1116.

Callan, T., Lyons, S., Scott, S., Tol, R. S., and Verde, S. (2009). The distributional implications of a carbon tax in Ireland. *Energy Policy*, 37(2):407–412.

Carattini, S., Kallbekken, S., and Orlov, A. (2019). How to win public support for a global carbon tax. *Nature*, 8:289–291.

Chichilnisky, G. and Heal, G. (1994). Who should abate carbon emissions?: An international viewpoint. *Economics Letters*, 44(4):443–449.

Cowell, F. (2011). *Measuring Inequality*. Oxford University Press.

D'Autume, A., Schubert, K., and Withagen, C. (2016). Should the carbon price be the same in all countries? *Journal of Public Economic Theory*, 18(5):709–725.

Davies, J. B., Shi, X., and Whalley, J. (2014). The possibilities for global inequality and poverty reduction using revenues from global carbon pricing. *The Journal of Economic Inequality*, 12:363–391.

Dechezleprêtre, A., Fabre, A., Kruse, T., Planterose, B., Chico, A. S., and Stantcheva, S. (2022). Fighting climate change: International attitudes toward climate policies. Working Paper WP30265, National Bureau of Economic Research.

Dell, M., Jones, B. F., and Olken, B. A. (2012). Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics*, 4(3):66–95.

Dellink, R., den Elzen, M., Aiking, H., Bergsma, E., Berkhout, F., Dekker, T., and Gupta, J. (2009). Sharing the burden of financing adaptation to climate change. *Global Environmental Change*, 19:411–421.

Dennig, F., Budolfson, M. B., Fleurbaey, M., Siebert, A., and Socolow, R. H. (2015). Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences of the United States of America*, 112(52):15827–15832.

Engström, G. and Gars, J. (2015). Optimal taxation in the macroeconomics of climate change. *Annu. Rev. Resour. Econ.*, 7(1):127–150.

Errickson, F., Rennels, L., Anthoff, D., and Dennig, F. (2022). The fairv2.0 simple climate model (julia). https://github.com/FrankErrickson/MimiFAIRv2.jl.

Feindt, S., Kornek, U., Labeaga, J. M., Sterner, T., and Ward, H. (2021). Understanding regressivity: Challenges and opportunities of european carbon pricing. *Energy Economics*, 103:105550.

Felder, S. and van Nieuwkoop, R. (1996). Revenue recycling of a CO2 tax: Results from a general equilibrium model for Switzerland. *Annals of Operations Research*, 68(2):233–265.

Fleurbaey, M. and Kornek, U. (2021). When redistribution makes personalized pricing of externalities useless. *Journal of Public Economic Theory*, 23(2):363–375.

Fragkos, P., Fragkiadakis, K., Sovacool, B., Paroussos, L., Vrontisi, Z., and Charalampidis, I. (2021). Equity implications of climate policy: Assessing the social and distributional impacts of emission reduction targets in the European Union. *Energy*, 237:121591.

Fujimori, S., Hasegawa, T., and Oshiro, K. (2020). An assessment of the potential of using carbon tax revenue to tackle poverty. *Environmental Research Letters*, 15(11):114063.

Garaffa, R., Cunha, B. S., Cruz, T., Bezerra, P., Lucena, A. F., and Gurgel, A. C. (2021). Distributional effects of carbon pricing in Brazil under the Paris Agreement. *Energy Economics*, 101:105396.

Gazzotti, P. (2022). RICE50+: DICE model at country and regional level. *Socio-Environmental Systems Modelling*, 4:18038.

Gewirtzman, J., Natson, S., Richards, J.-A., Hoffmeister, V., Durand, A., Weikmans, R., Huq, S., and Roberts, J. T. (2018). Financing loss and damage: reviewing options under the warsaw international mechanism. *Climate Policy*, 18(8):1076–1086.

Hourcade, J.-C. and Gilotte, L. (2000). Differentiated or uniform international carbon taxes: Theoretical evidences and procedural constraints. In *Environmental markets*, pages 135–155. Columbia University Press.

INFORM (2022). Inform risk index 2023. Data retrieved from https://drmkc.jrc.ec.europa.eu/inform-index.

Jakob, M., Chen, C., Fuss, S., Marxen, A., Rao, N. D., and Edenhofer, O. (2016). Carbon pricing revenues could close infrastructure access gaps. *World Development*, 84:254–265.

Kalkuhl, M. and Wenz, L. (2020). The impact of climate conditions on economic production. evidence from a global panel of regions. *Journal of Environmental Economics and Management*, 103:102360.

Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., and Stern, N. (2018). Making carbon pricing work for citizens. *Nature Climate Change*, 8:669–677.

Köppl, A. and Schratzenstaller, M. (2022). Carbon taxation: A review of the empirical literature. *Journal of Economic Surveys*, forthcoming.

Leach, N. J., Jenkins, S., Nicholls, Z., Smith, C. J., Lynch, J., Cain, M., Walsh, T., Wu, B., Tsutsui, J., and Allen, M. R. (2021). Fairv2. 0.0: a generalized impulse response model for climate uncertainty and future scenario exploration. *Geoscientific Model Development*, 14(5):3007–3036.

Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S. J., Freeman, S., Forster, P. M., Fuglestvedt, J., et al. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, 244:117834.

Liang, Q.-M. and Wei, Y.-M. (2012). Distributional impacts of taxing carbon in China: Results from the CEEPA model. *Applied Energy*, 92:545–551.

Marin-Ferrer, M., Vernaccini, L., and Poljansek, K. (2017). Index for risk management inform concept and methodology report – version 2017. Technical report, EUR 28655.

Nordhaus, W. D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 114:1518–1523.

Nordhaus, W. D. and Yang, Z. (1996). A regional dynamic general-equilibrium model of alternative climate-change strategies. *The American Economic Review*, 86(4):741–765.

Ohlendorf, N., Jakob, M., Minx, J. C., Schröder, C., and Steckel, J. C. (2021). Distributional impacts of carbon pricing: A meta-analysis. *Environmental and Resource Economics*, 78:1–42.

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., et al. (2016). The scenario model intercomparison project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, 9(9):3461–3482.

Pinkovskiy, M. and Sala-i Martin, X. (2009). Parametric Estimations of the World Distribution of Income. Working Paper 15433, National Bureau of Economic Research.

Rao, N. D., Sauer, P., Gidden, M., and Riahi, K. (2018). Income inequality projections for the Shared Socioeconomic Pathways (SSPs). *Futures*, 105:27–39.

Rausch, S., Metcalf, G. E., and Reilly, J. M. (2011). Distributional impacts of carbon pricing: A general equilibrium approach with micro-data for households. *Energy Economics*, 33:S20–S33.

Ravigné, E., Ghersi, F., and Nadaud, F. (2022). Is a fair energy transition possible? Evidence from the French low-carbon strategy. *Ecological Economics*, 196:107397.

Riahi, K., Bertram, C., Huppmann, D., Rogelj, J., Bosetti, V., Cabardos, A.-M., Deppermann, A., Drouet, L., Frank, S., Fricko, O., et al. (2021). Cost and attainability of meeting stringent climate targets without overshoot. *Nature Climate Change*, 11(12):1063–1069.

Roberts, J. T., Natson, S., Hoffmeister, V., Durand, A., Weikmans, R., Gewirtzman, J., and Huq, S. (2017). How will we pay for loss and damages? *Ethics, Policy and Environment*, 20(2):208–226.

Robinson, S.-A., Khan, M., Roberts, J. T., Weikmans, R., and Ciplet, D. (2021). Financing loss and damage from slow onset events in developing countries. *Current Opinion in Environmental Sustainability*, 50:138–148.

Sandmo, A. (2006). Global public economics: Public goods and externalities. *Économie publique/Public economics*, 2006/1-2(18-19):3–21.

Soergel, B., Kriegler, E., Bodirsky, B. L., Bauer, N., Leimbach, M., and Popp, A. (2021). Combining ambitious climate policies with efforts to eradicate poverty. *Nature Communications*, 12:2342.

Steckel, J. C., Dorband, I. I., Montrone, L., Ward, H., Missbach, L., Hafner, F., Jakob, M., and Renner, S. (2021). Distributional impacts of carbon pricing in developing Asia. *Nature Sustainability*, 4(11):1005–1014.

Tol, R. S. (2001). Equitable cost-benefit analysis of climate change policies. *Ecological Economics*, 36:71–85.

Tol, R. S. (2002). Welfare specifications and optimal control of climate change: an application of FUND. *Energy Economics*, 24:367–376.

Traut, M., Larkin, A., Anderson, K., McGlade, C., Sharmina, M., and Smith, T. (2018). CO2 abatement goals for international shipping. *Climate policy*, 18(8):1066–1075.

UNFCCC (2015). Report of the conference of the parties on its twenty-first session, held in paris from 30 november to 13 december 2015. Report FCCC/CP/2015/10/Add.1, United Nations Framework Convention on Climate Change.

United Nations Department of Economic and Social Affairs, Population Division (2022). World Population Prospects 2022: Summary of Results. Report UN DESA/POP/2022/TR/NO. 3.

Vogt-Schilb, A., Walsh, B., Feng, K., Di Capua, L., Liu, Y., Zuluaga, D., Robles, M., and Hubaceck, K. (2019). Cash transfers for pro-poor carbon taxes in Latin America and the Caribbean. *Nature Sustainability*, 2(10):941–948.

Williams, R. C., Gordon, H., Burtraw, D., Carbone, J. C., and Morgenstern, R. D. (2015). The initial incidence of a carbon tax aross income groups. *National Tax Journal*, 68(1):195–213.

Young-Brun, M. (2023). Public acceptability of carbon taxation: a model of political support with income and urban-rural inequality. Mimeo, Paris School of Economics.

A Appendix

A.1 Abatement cost

For country i at time t, the cost of abatement in terms of share of gross output is

$$\Lambda_{it} = \theta_{1,it}\mu_{it}^{\theta_2} \tag{A.1.1}$$

with μ_{it} abatement rate, $\theta_{1,it}$ country-specific parameters and $\theta_2 = 2.6$. It follows that the cost of abatement in dollars per unit of emission is

$$C_{it}(\mu_{it}) = \frac{\Lambda_{it}Y_{it}}{E_{it}} \tag{A.1.2}$$

$$= \frac{\theta_{1,it}\mu_{it}^{\theta_2}}{\sigma_{it}} \tag{A.1.3}$$

with σ_{it} the emissions intensity of country i.

We compute $\theta_{1,it}$ for each country from the global price per tCO2 that enables full decarbonization (backstop price) such that

$$\frac{\partial C_{it}}{\partial \mu_{it}}(1) = p_t^{backstop}, \tag{A.1.4}$$

which results in

$$\theta_{1,it} = p_t^{backstop}\frac{\sigma_{it}}{\theta_2}. \tag{A.1.5}$$

We use the trajectory of the price for full decarbonization from Nordhaus & Barrage (2023), who perform a statistical analysis on the ENGAGE study (Riahi et al., 2021). Converted into 2017US$ per tCO2, this implies a backstop price of 495 2017US$ per tCO2 in 2050. We also assume the backstop price decreases by 1% by year betwen 2020 and 2050, and by 0.01% after 2050. This results in a price for full decarbonization in 2020 of 670 2017US$.

A.2 Damage functions

Assume that the share of damages (as a fraction of gross GDP in a country) is given by:

$$\delta(T) = 1 - e^{-\beta_1 T - \beta_2 T^2}, \tag{A.2.1}$$

with T the average annual temperature in the country, and $\delta(T)$ the share of damages.

To calibrate parameters β_1 and β_2, we use the results by Kalkuhl and Wenz (2020) on the reduction of economic output from a 1°C increase in temperature. (Kalkuhl and Wenz, 2020, Table 9) obtain that, in their preferred econometric specification, a 1°C increase in temperature implies a 0.8% in output when the initial temperature is 10°C. And they obtain that 1°C increase in temperature implies a 3.5% in output when the initial temperature is 25°C. From these numbers, we obtain $\beta_1 = -0.01128$ and $\beta_2 = 0.00092$.

Next, we want to compute country-specific damage functions that depends on the climate anomalies from pre-industrial temperature in that region, that we denote $\bar{T}_i$, where i is the index for the country. Remark that we have:

$$\big(1 - \delta(T)\big) = \tfrac{1-(\delta(T)-\delta(\bar{T}_i))-\delta(\bar{T}_i)}{1-\delta(\bar{T}_i)}\big(1 - \delta(\bar{T}_i)\big) \tag{A.2.2}$$

The share $\delta(\bar{T}_i)$ would be lost anyway in the absence of climate change (when the climate anomaly is nil), so the share of output lost in country i due to climate change is simply:

$$\delta_i(T) = 1 - \frac{1-\delta(T)}{1-\delta(\bar{T}_i)} = 1 - e^{-\beta_1(T-\bar{T}_i)-\beta_2(T^2-(\bar{T}_i)^2)}. \tag{A.2.3}$$

This can be written as a function of the local temperature anomaly, $\Delta_i T = T - \bar{T}_i$:

$$\delta_i(\Delta_i T) = 1 - e^{-\beta_1\Delta_i T-\beta_2(\Delta_i T)^2-2\beta_2\bar{T}_i\Delta_i T} \approx (\beta_1 + 2\beta_2\bar{T}_i)\Delta_i T + \beta_2(\Delta_i T)^2. \tag{A.2.4}$$

We thus obtain the country-specific damage function $\delta_i(\Delta_i T) = \beta_{i1} \cdot \Delta_i T + \beta_{i2} \cdot (\Delta_i T)^2$, with $\beta_{i1} = \beta_1 + \beta_2\bar{T}_i$ and $\beta_{i2} = \beta_2$. To calibrate parameters β_{i1} and β_{i2}, we only need to know parameters β_1 and β_2(already calibrated above) and the local pre-industrial temperature.

For the local pre-industrial temperature, we use the average annual temperature in the country for the period 1900-1909, based on the population weighted temperature in Dell et al. (2012). The temperature in period 1900-1909 is not significantly different from the pre-industrial temperature at the global level, hence the choice of the period.

A.3 A simple model of optimally differentiated carbon tax

Assume that there is a set of countries $I = \{1, \cdots, n\}$, with i the index of the country and consider a specific period t. Assume that we have the objective to emit at most E_t at the global level. How should emissions be shared between the different countries?

To answer the question, let Y_{it} be the gross production in country i at period t. We assume that pre-abatement emissions in that country are given by $E_{it} = \sigma_{it}Y_{it}$, with σ_{it} a technology parameter that relates (gross) production to emissions. We want to define the optimal emissions in the country. For an abatement effort μ_{it}, the emissions in the country will be $(1 - \mu_{it})E_{it}$.

The abatement cost (as a share of gross production) is given by a function $\Lambda_{it}(\mu_{it})$ that depends on the abatement effort μ_{it}.[8] Given the population N_{it} in the region, per capita consumption is given by:

$$c_{it} = (1 - s_{it})\big(1 - \Lambda_{it}(\mu_{it})\big)\frac{Y_{it}}{N_{it}}, \tag{A.3.1}$$

with s_{it} the savings rate in the country.

We assume that we want to fix optimal abatement efforts that maximize the sum of utilities from consumption. The objective is thus to maximize

$$\sum_i N_{it}u(c_{it})$$

with the constraint that the sum of emissions is less than E_t: $\sum_i(1 - \mu_{it})E_{it} \leq E_t$.

Using the equations above, we obtain the following maximization problem:

$$\begin{array}{ll} \max\limits_{(\mu_{it})_i} & \sum_i N_{it}u\left((1 - s_{it})\Big(1 - \Lambda_{it}(\mu_{it})\Big)\frac{Y_{it}}{N_{it}}\right) \\ s.t. & \sum_i(1 - \mu_{it})\sigma_{it}Y_{it} \leq E_t \end{array}$$

[8]We write $\Lambda_{it}(\mu_{it})$ instead of Λ_{it} that we used in Section to make explicit the dependence on μ_{it}, given that we will maximize with respect to the abatement effort.

The first order condition with respect to each μ_{it} yields:

$$(1-s_{it})\frac{\partial\Lambda_{it}/\partial\mu_{it}}{\sigma_{it}}u'(c_{it})=\lambda,$$

with λ the multiplier associated with the constraint.

Denote τ_{it} the carbon tax in country i. The abatement cost per emission in the model is $C_{it}(\mu_{it})=\frac{\Lambda_{it}(\mu_{it})Y_{it}}{E_{it}}=\frac{\Lambda_{it}(\mu_{it})}{\sigma_{it}}$. In equilibrium, the carbon tax should be equal to the marginal abatement cost per emission, so we should have $\tau_{it}=C'_{it}(\mu_{it})=\frac{\partial\Lambda_{it}/\partial\mu_{it}}{\sigma_{it}}$. We obtain a formula for the optimal level of the carbon tax in country i at period t:

$$\tau_{it}=\frac{(1-s_{it})}{(1-s_{1t})}\frac{u'(c_{1t})}{u'(c_{it})}\tau_{1t}. \tag{A.3.2}$$

Thus, we have a relation between the tax rate in any country and the tax rate in the first country that we take as a reference.

Also, as mentioned before, we assume that $\Lambda_{it}=\theta_{1,it}\mu_{it}^{\theta_2}$. We also assume that $u(c)=c^{1-\eta}/(1-\eta)$ (see the next section). So, from previous results we see that mitigation efforts at the country-level are controlled by the level of carbon tax in the reference country. Indeed:

$$\frac{\theta_2\theta_{1,it}}{\sigma_{it}}\mu_{it}^{\theta_2-1}=\frac{\partial\Lambda_{it}/\partial\mu_{it}}{\sigma_{it}}=\frac{(1-s_{it})}{(1-s_{1t})}\frac{u'(c_{1t})}{u'(c_{it})}\tau_{1t},$$

so that (also using that $\theta_{1,it}=p_t^{backstop}\frac{\sigma_{it}}{\theta_2}$ in our calibration):

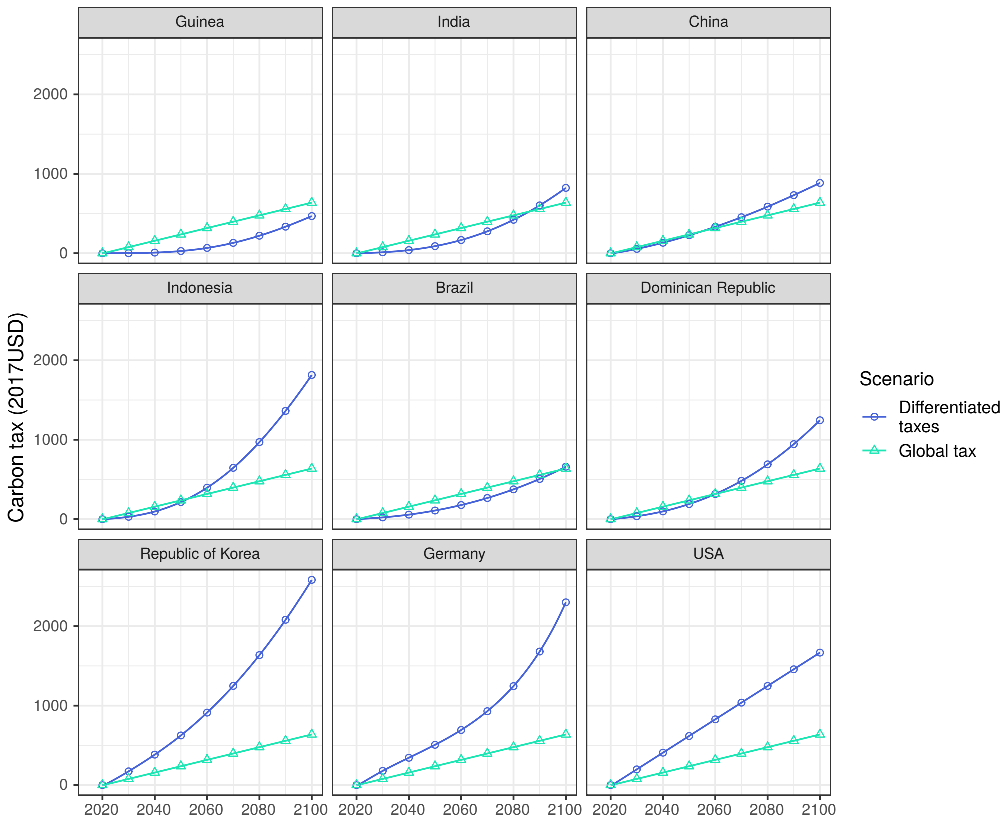
$$\mu_{it}=\left(\frac{(1-s_{it})}{p_t^{backstop}\times(1-s_{1t})}\frac{c_{1t}^{-\eta}}{c_{it}^{-\eta}}\tau_{1t}\right)^{\frac{1}{\theta_2-1}}.$$

To close the model, we do not use c_{it} as defined above but the approximation by:

$$\tilde{c}_{it}=(1-s_{it})\frac{Y_{it}}{N_{it}}.$$

A.4 Carbon tax trajectories for selected countries

Figure A.1: Carbon taxes (USD/tCO_2) for a selection of countries, for the 2°C scenarios implemented via a global uniform tax (blue green) and via differentiated taxes across countries (dark blue).



A.5 List of low and low-middle income countries

Low income countries: Afghanistan, Burundi, Burkina Faso, Central African Republic, Democratic Republic of the Congo, Eritrea, Ethiopia, Guinea, The Gambia, Guinea-Bissau, Liberia, Madagascar, Mali, Mozambique, Malawi, Niger, The Democratic People's Republic of Korea, Rwanda, Sudan, Sierra Leone, Somalia, South Sudan, Syrian Arab Republic, Chad, Togo, Uganda, Yemen, Republic of Zambia.

Low-middle income countries: Angola, Benin, Bangladesh, Bolivia, Bhutan, Côte d'Ivoire, Cameroon, Republic of the Congo, Comoros, Cabo Verde, Djibouti, Algeria, Arab Republic of Egypt, Federal States of Micronesia, Ghana, Honduras, Haiti, Indonesia, India, Islamic Republic of Iran, Kenya, Kyrgyz Republic, Cambodia, Kiribati, Lao People's Democratic Republic, Lebanon, Sri Lanka, Lesotho, Morocco, Myanmar, Mongolia, Mauritania, Nigeria, Nicaragua, Nepal, Pakistan, Philippines, Papua New Guinea, West Bank and Gaza, Senegal, Solomon Islands, El Salvador, São Tomé and Príncipe, Eswatini, Tajikistan, Timor-Leste, Tunisia, Tanzania, Ukraine, Uzbekistan, Vietnam, Vanuatu, Samoa, Zimbabwe.

A.6 Constructing a climate risk index

The risk index used to distribute Loss and Damage funding among poorer countries is based on the INFORM Risk Index. The objective of the INFORM Risk Index is to identify the countries at a high risk of humanitarian crisis that are more likely to require international assistance. Specifically, the index is designed to facilitate an objective allocation of resources for disaster management as well as for coordinated actions focused on anticipating, mitigating, and preparing for humanitarian emergencies.

The INFORM Risk Index is based on an methodology also discussed by the IPCC that considers three dimensions of risk: Hazards & Exposure, Vulnerability and Lack of Coping Capacity. For each of these dimensions, a normalized index (between 0 and 1) is constructed based on a number of other indicators. Then the three dimensions are combined using a geometric mean.

In the paper we use a modified version of the INFORM index designed to take into account only climate-related natural risks. We thus only modify the Hazards & Exposure index that we compute as a combination (through a geometric mean) of three indices for specific climate-related natural risks: flood, tropical cyclone, and drought. We combine our new index for Hazards & Exposure at the country level with the INFORM country indices for Vulnerability and Lack of Coping Capacity. Our computations use the latest release of the INFORM Risk Index dataset (INFORM, 2022).

A.7 Welfare measurement via equally distributed equivalent consumption

Instantaneous welfare in country i and period t is

$$\frac{P_{it}}{N_q}\sum_q \frac{c_{iqt}^{1-\eta}}{1-\eta} \tag{A.7.1}$$

with N_q the number of quantiles and η inequality aversion.

Instantaneous equally distributed equivalent consumption (Atkinson, 1970) in country i is defined as the level $c_{EDE,it}$ such that

$$\frac{P_{it}}{N_q}\sum_q \frac{c_{EDE,t}^{1-\eta}}{1-\eta} = \frac{P_{it}}{N_q}\sum_q \frac{c_{iqt}^{1-\eta}}{1-\eta}. \tag{A.7.2}$$

Hence,

$$c_{EDE,it} = \left(\frac{1}{N_q}\sum_q c_{iqt}^{1-\eta}\right)^{\frac{1}{1-\eta}} \tag{A.7.3}$$

Denote $\bar{c}_{it}$ the average consumption in country i and period t, remark that we have the following decomposition:

$$c_{EDE,it} = \bar{c}_{it} \times \left(\frac{1}{N_q}\sum_q \left(\frac{c_{iqt}}{\bar{c}_{it}}\right)^{1-\eta}\right)^{\frac{1}{1-\eta}} = \bar{c}_{it} \times (1 - A_{it}^{\eta}),$$

where A_{it}^{η} is the so-called Atkinson inequality index for consumption in country i and period t. So, we can decompose the welfare effect into an effect on average consumption and an effect on inequality (Atkinson, 1970).

We can also compute welfare at the global level. The global equally distributed equivalent consumption is defined as $c_{EDE,t}$ such that

$$\sum_i \frac{P_{it}}{N_q} \sum_q \frac{c_{EDE,t}^{1-\eta}}{1-\eta} = \sum_i \frac{P_{it}}{N_q} \sum_q \frac{c_{iqt}^{1-\eta}}{1-\eta}. \tag{A.7.4}$$

Resulting in

$$c_{EDE,t} = \left(\frac{\sum_i \frac{P_{it}}{N_q} \sum_q c_{iqt}^{1-\eta}}{\sum_i P_{it}} \right)^{\frac{1}{1-\eta}} \tag{A.7.5}$$

$$= \left(\frac{\sum_i P_{it} (c_{EDE,it})^{1-\eta}}{\sum_i P_{it}} \right)^{\frac{1}{1-\eta}} \tag{A.7.6}$$

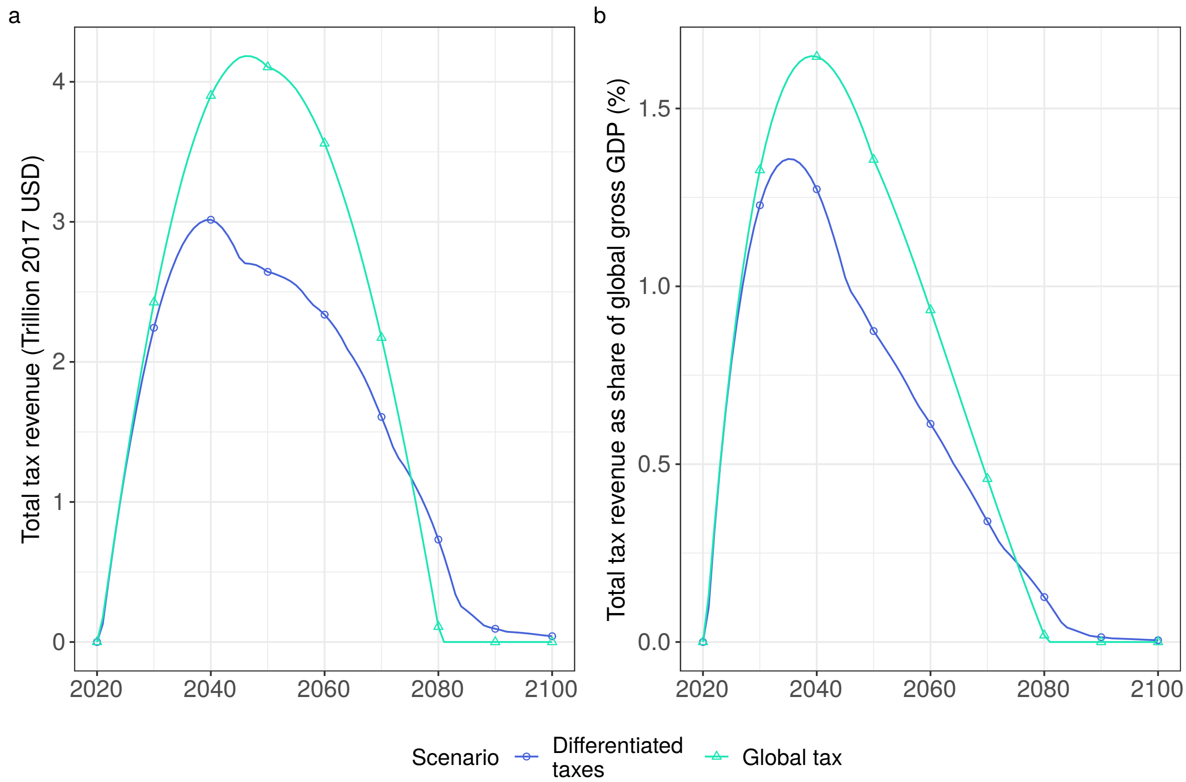
Denoting $\bar{c}_t$ the average consumption at the global level in period t, we again obtain the Atkinson decomposition:

$$c_{EDE,t} = \bar{c}_t \times \left(\frac{\sum_i \frac{P_{it}}{N_q} \sum_q \left(\frac{c_{iqt}}{\bar{c}_t} \right)^{1-\eta}}{\sum_i P_{it}} \right)^{\frac{1}{1-\eta}} = \bar{c}_t \times (1 - A_t^\eta),$$

where A_t^η is the Atkinson inequality index for global consumption in period t.

A.8 Global revenues from the carbon tax

Figure A.2: Global carbon tax revenues in the 2°C scenario, in a) trillion 2017USD, and b) share of global gross output (%).



A.9 Sensitivity analysis: inequality aversion

Figure A.3: Difference in the equally distributed equivalent (EDE) consumption in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives, and $\eta = 1$.
Note: we use the same differentiated taxes pathways as in the main analysis.