The Distributional Effects of Carbon Pricing: A Global View of Common but Differentiated Responsibilities

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Abstract

We use a quantitative international trade model with climate policies to explore the idea of Common but Differentiated Responsibilities (CBDR), a leading principle of climate action. The principle recognizes that low- and middle-income countries are most affected by climate change despite their lower contributions to its causes. We investigate the consequences for global equity of policies that ignore CBDR and explore the efficiency and feasibility of various policy schemes that comply with the principle. Our analysis delivers three main results. First, we document that efficient climate policies that ignore CBDR strongly exacerbate between-country inequality. Second, we show that equity can still be achieved with efficient climate policies when they are paired with realistic international transfers that either socialize the costs of carbon taxation or account for historical emission patterns with a modest impact on the population of high-income countries. Third, we show that carbon taxation schemes that rely on heterogeneous pricing with lower taxes for low and middle-income countries do not necessarily lead to fairer outcomes.

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1 Introduction

Climate change is one of the most pressing challenges of our time. It is driven by greenhouse gas (GHG) emissions, a pure externality that impacts all nations, though not in the same way. In particular, low- and middle-income countries are more vulnerable to climate hazards[1], which contrasts with their historically lower contribution to the cumulative stocks of GHG in the atmosphere. This difference led the Global South to push over time for differentiated contributions to the solution of the climate crisis that acknowledge that they suffer the most while having contributed the least to the problem. Such efforts, however, have not been particularly successful in being translated into actual policies. In reality, opposition to this reasoning is often pointed out as one of the main motives why climate negotiations fail to deliver effective outcomes.

Despite its contentious character, the idea that low- and middle-income countries have different responsibilities in the fight against climate change is today one of the leading principles of climate action steering high-level climate talks, such as the Conference of the Parties (COP) meetings. In fact, this notion has been well-established for three decades, first formalized in the United Nations Framework Convention on Climate Change (UNFCCC) of Earth Summit in Rio de Janeiro in 1992, with the principle of Common but Differentiated Responsibilities (CBDR). In essence, it acknowledges that all states have a shared obligation to address environmental destruction but denies equal responsibility to all states about environmental protection. Although more than 30 years old, the principle has recently been brought back to the center of climate negotiations in the context of the Paris Agreements, remaining a polarizing policy to date. For instance, to much of the frustration of low- and middle-income parties, CBDR was not explicitly mentioned on the final text of the 2023 COP meeting in Doha after the opposition of high-income countries.[2]

In this paper, we aim to inform this debate about climate action and global equity by conducting the first comprehensive quantitative analysis of the principle of Common but Differentiated Responsibilities (CBDR). We use a state-of-the-art quantitative trade model with climate policies to explore the case for differentiated contributions in the fight against climate change, as well as their political

[1]The vulnerability of developing countries to the effects of climate change has been demonstrated repeatedly by the Intergovernmental Panel on Climate Change (IPCC) in the report of their second working group (Adler et al., 2022).

[2]According to the website Carbon Brief on their discussion about the outcomes of the COP meeting in Doha, "Many developing countries wanted to acknowledge the [CBDR] principle in the Global Goal on Adaptation (GGA) talks. (...) Developed countries, on the other hand, completely opposed its inclusion." GGA is a "a "framework" that is meant to guide nations in their efforts to protect their people and ecosystems from climate change." (Brief, 2023)

viability. To structure the analysis, we first establish a benchmark that asks what are the consequences of climate policies that disregard geopolitical considerations and, more specifically, the CBDR principle and document their uneven impact on low- and middle-income countries. This involves the adoption of a single global price for CO_2 equivalents (CO_2e), a Pigouvian-style tax that economists have long advocated as the optimal climate policy.[3]

Next, we ask how equity could be then achieved in the presence of optimal taxes. We explore various international transfer schemes that either socialize the current costs of carbon taxation or account for historical cross-country emission patterns in the spirit of the CBDR. This allows us to shed light on the feasibility of climate policies that both deliver efficiency and ensure a politically desirable redistribution of the costs of climate action. Finally, we investigate some mainstream proposals for carbon taxation that rely on heterogeneous pricing and ask what are their implications for climate justice by comparing them to a global and uniform policy benchmark. We investigate two policy options: a unilateral carbon pricing scheme amongst a selected "club" of countries with a Carbon Border Adjustment Mechanism (CBAM) and heterogeneous carbon prices based on income levels following a recent proposal by the International Monetary Fund (IMF)(Parry et al., 2021).

Our analysis builds on a modern general equilibrium international trade model. It features multiple countries and sectors and a detailed description of the world economy, including trade in final and intermediate goods, sectoral heterogeneity, and input-output linkages (Armington, 1969; Caliendo and Parro, 2015).[4] It includes 64 countries and regions and 45 tradable and non-tradable sectors. We leverage rich data on CO_2, CH_4, and N_2O emissions, which capture 93% of all GHG emissions. In the model, governments have access to an option of climate policy, a carbon tax paid by consumers and firms when purchasing final and intermediate goods. Our benchmark policy is a 100 USD/tCO_2e carbon tax.[5]

[3]As noted by Blanchard et al. (2023), economists largely agree that a pigouvian tax is indispensable in the fight against climate change despite its unpopularity. We use a uniform global carbon tax as a benchmark for policies that disregard CBDR because this is the optimal policy in a perfectly competitive environment, such as the one we consider in our analysis. We derive the optimal carbon tax in a stripped down version of our quantitativer setup in Appendix D. See Farrokhi and Lashkaripour (2021) for a characterization of optimal climate policies in a different setup.

[4]We work with an Armington (1969) model with input-output linkages to capture the complexity of real-world production chains. It is now well understood that this model makes the same aggregate predictions as richer quantitative trade models such as Eaton and Kortum (2002).

[5]As explained by Blanchard et al. (2023), under the Pigouvian approach, the price of 1 ton of CO2 should be equal to the social cost of carbon, or the discounted value of the flow of damages it generates. However, "there exists no consensus among economists about how large this Pigouvian carbon price should be." We use a 100 USD/tCO_2e carbon tax because its closer to policy discussions and actual policies, such as the price of carbon at the EU Emissions Trading System.

Our results show that a uniform carbon tax strongly exacerbates between-country inequality. While it is commonly accepted that low-income countries are affected the most by climate change (Adler et al., 2022), our analysis implies that these countries also bear most of the costs of climate action. This is a common perception surrounding climate talks, which our quantitative analysis allows us to put numbers on. At first glance, carbon taxes are an effective climate policy, with a 100 USD/tCO_2e carbon tax decreasing emissions by 28% at a real income loss of only 0.7% on average. However, the low average real income losses mask a significant degree of heterogeneity across countries. Low- and middle-income countries experience real income losses of up to 7%, while high-income countries often experience a real income gain.

These results are driven by the fact that the Global South tends to specialize in more polluting industries and produce using polluting technologies, so the effective tax burden on these countries is more severe. Accordingly, effective tax rates translate into 1-2% taxes for high-income countries and up to 8% for low-income countries. These differences imply that carbon taxes induce reallocation of economic activity towards greener sectors and greener-origin countries due to international trade and global value chains, all of which are disproportionately located in high-income markets. Moreover, a global carbon policy means that a larger share of labor is reallocated within low and middle-income countries, which adds to their costs of climate adaptation.

Given that some countries experience a real income gain while others face a real income loss, there is a role for international transfers to equalize the economic costs of climate action. Our headline result is that realistic cross-country transfers of an average of USD200 per person from the Global North to the Global South could remedy this inequality while allowing for substantial emissions reduction led by the common carbon tax. We obtain this result from two different scenarios. The first explores equal-cost transfers, which equalize real income losses from carbon taxation. Similar to climate action without redistribution, this scenario generates a decrease in global emissions of 28%, but this time with uniform international real income costs of 0.7%. The largest payers would be European countries and the U.S. and the largest receivers are large low- and middle-income countries, such as Kazakhstan, Russia, South Africa, and Southeast Asian countries. In total, equal-cost transfers would amount to USD 272 bn, which would involve tripling the current transfers provided by high-income countries for climate finance (OECD, 2022). While this is a substantial amount, its impact on the population of developed countries is in fact relatively modest. The highest transfers would need to be paid by Ireland in the amount of

USD 2,000 per person per year. For the rest of the EU members and the U.S., the effective amount that should be paid by an individual in a year does not exceed USD 1,000.

The second type of transfer is a polluter-pays transfer, which aims to quantitatively simulate the CBDR principle by making the realized real-income cost borne by a country proportional to its historical contribution to global cumulative emissions. This scenario delivers three main results. First, the total amount of transfers required is slightly lower than in the equal-cost scenario, at USD 255.7 billion, because the polluter-pays scheme allows for unequal economic costs based on historical responsibility. Second, the distribution of transfers across countries still implies that high-income countries should pay and low- and middle-income countries should receive. This should not be a surprise as countries that benefited from the Industrial Revolution started to emit CO_2 during the 19th century and now have the highest levels of development.

Third, the relative contributions of countries change to reflect individual countries' weight in historical emissions. This is, for example, the case of Russia. Because Russia is a large producer of natural gas, it is heavily penalized by the carbon tax. In the equal costs scenario, Russia received transfers of the order of USD 404 per capita to bring its real-income cost up to par with other countries. Russia is, however, also a historical polluter, so in the polluter-pays scenario, its effective per-capita transfers decrease to less than USD 80 per person per year. One constant in the comparison between the two scenarios is that countries that were receivers in the equal-costs scenario remain receivers in the polluter pays scenario, and payers remain payers. This suggests that a polluter-pays scheme could perhaps be a better redistribution mechanism: fairness is still somewhat achieved while respecting the politically desired principle of Common but Differentiated Responsibilities.

Last, we find that while heterogeneous pricing schemes such as a climate club with a CBAM and the recent IMF carbon taxation proposal may be politically more feasible, they do not necessarily lead to fairer outcomes. Specifically, a climate club scenario with a CBAM that involves key global players necessary to deliver meaningful reduction in emissions requires significantly higher North-South transfers compared to the uniform tax scenario and is less efficient. Similarly, the IMF's International Carbon Floor Pricing, especially when limited to major emitters, results in greater welfare costs and slightly higher North-South transfers than a uniform carbon tax. Broadening participation in the IMF scheme does improve fairness and efficiency, suggesting that more inclusive approaches may lead to better outcomes in terms of equity and cost-effectiveness. In sum, our findings challenge the notion that differentiated carbon pricing is inherently fairer and highlight the complexities involved in designing policies that achieve both fairness and efficiency in global climate action.

This paper contributes to several strands of the literature.

Trade policy and GHG emissions Our study adds to the extensive literature on trade policy and greenhouse gas emissions. Earlier studies focused on small-scale models (Markusen, 1975; Hoel, 1996; Copeland, 1996). Most papers analyze the effects of unilateral climate policy on trade, notably on leakage (Felder and Rutherford, 1993; Babiker, 2005; Elliott et al., 2010, 2012; Aichele and Felbermayr, 2012; Hémous, 2016; Böhringer et al., 2016; Kortum and Weisbach, 2021; Weisbach et al., 2023; Larch and Wanner, 2017, 2024).

The two closest papers in this literature are Farrokhi and Lashkaripour (2021) and Klotz and Sharma (2023). Farrokhi and Lashkaripour (2021) analyze the efficacy of trade policies, specifically carbon border taxes and a climate club with trade penalties, as tools to enforce global climate cooperation and reduce carbon emissions. The paper concludes that carbon border taxes alone are largely ineffective, achieving a modest reduction in global emissions, while a climate club led by major economies could significantly cut global emissions by fostering wider international cooperation. Klotz and Sharma (2023) discuss the impacts of reducing trade barriers, such as tariffs and transportation costs, on global CO_2 emissions. They focus on how changes in transportation and the use of intermediate inputs influence emissions, showing that reductions in trade barriers generally lead to an increase in global emissions through an increase in transportation emissions and changes in the composition of production towards more emissions-intensive activities. In contrast, our contribution lies in focusing on the socioeconomic impacts of global climate policies on low and middle-income regions and exploring solutions to offset these impacts, thus addressing an equity dimension often overlooked in broader analyses of trade and environmental policies.

Distributional effects of climate change and carbon policies The literature on the distributional effects of climate change is an active area of research. Krusell and Smith (2022) use an Integrated Assessment Model to show that the impacts of climate change vary strongly across different regions. Kotlikoff et al. (2021) investigate the potential for uniformly beneficial outcomes from carbon taxation across different regions and generations, using an overlapping generations model. The model evaluates the effects of a carbon tax coupled with generation- and region-specific transfers. The study finds that such a policy can mitigate the adverse economic impacts of climate change, with potential welfare improvements for all current and future individuals across different regions. We complement this paper by focusing on the impact of climate policy on different countries as opposed to different generations.

Closest to our study are Cavalcanti et al. (2020) and Finkelstein Shapiro and Nuguer (2023). Cavalcanti et al. (2020) evaluate the aggregate and distributional effects of climate change mitigation policies in a closed-economy general equilibrium model, specifically focusing on the impacts of carbon taxes across different sectors. The results highlight that such policies have uneven effects across sectors and disproportionately affect workers in high-carbon industries, with significant welfare losses compared to those in other sectors. Finkelstein Shapiro and Nuguer (2023) examine the impacts of a carbon tax on labor markets and macroeconomic outcomes in emerging economies. They use a search and matching macroeconomic model that includes pollution externalities from energy production, endogenous green-technology adoption, and dynamics between formal and informal sectors. The authors find that a carbon tax leads to higher energy prices, reducing formal firm creation and increasing self-employment and informality. These changes cause a decline in GDP and welfare in the long run. They suggest combining a carbon tax with policies that reduce the cost of firm formality, which can mitigate these adverse effects and support a transition to a greener economy.

Both Cavalcanti et al. (2020) and Finkelstein Shapiro and Nuguer (2023) follow a closed economy approach and calibrate their models to a few countries only (US, China Brazil for Cavalcanti et al. (2020) and emerging economies for Finkelstein Shapiro and Nuguer (2023)). While their work focuses on within-country inequality and the effects on employment, we adopt a global perspective, covering distributional effects across all countries.

Integrated Assessment Models We also have points in contact with the Integrated Assessment Model literature (Nordhaus, 1993, 2018; Golosov et al., 2014; Boyce, 2018). Integrated Assessment Models also analyze the aggregate effects of climate change and climate policy on the economy. We add an international economics dimension to the benefits and costs of climate policy.

2 Model

In this section, we develop a static, multi-country, multi-industry general equilibrium model of international trade in which governments have an option of climate policy. International trade is modeled as in Armington (1969). The production structure accounts for trade in final and intermediate goods, sectoral heterogeneity, and input-output linkages, as in Caliendo and Parro (2015).[6]

There are $\mathcal{N}$ countries denoted by i (for origin) and j (for destination) producing a local-specific variety of $\mathcal{S}$ sectors denoted by s' (produced by origin i) and s (destination sector if in a value chain). Varieties of good s' produced by i and imported in country j are traded and subjected to iceberg trade costs $\tau_{is'j}$ such that $\tau_{is'i} = 1$. Countries are endowed with an exogenous inelastic supply of labor L_i that is internationally immobile.

2.1 Carbon tax

A carbon tax is imposed on each good or service produced in the economy. Consumers of final goods pay the tax when consuming the good, and producers pay the tax on intermediate inputs they use in production. The tax is paid in the final destination country (i.e. by importers) and redistributed within that country as a lump sum to consumers. In its most general form the tax is denoted $t^e_{is'j}$ where i denotes the origin country producing good or service s' destined for consumption in country j. It is meant to apply a price to each ton of carbon emitted such that

$$t^e_{is'j} = t_{is'j} * e_{is'}$$
$$e_{is'} = \frac{CO2_{is'}}{Y_{is'}}$$

with t denoting a dollar amount to be imposed on a ton of CO_2e (e.g. \$100) and $e_{is'}$ denoting the production emission intensity of production of good s' in country i.[7,8]

[6] It is well understood today that general equilibrium models with distinct microfoundations have the similar predictions in equilibrium (Arkolakis et al., 2012). In our case, our quantitative model would yield the same predictions as a more complex framework, such as, for instance, an Eaton and Kortum (2002) model with trade in intermediates. We keep the Armington (1969) assumption to simplify the exposition.

[7] Note that due to data restrictions, $e_{is'}$ is calculated in terms of tons of CO_2e emitted per \$ of output. In practice, because the tax $t^e_{is'j}$ is applied as an *ad valorem* tax it is equivalent to apply a per-unit tax on GHG emissions:

$$p_{is'j}\left(1 + t_{is'j} \times \frac{CO_{2,is'}}{p_{is'j}q_{is'j}}\right) q_{is'j} = p_{is'j}q_{is'j} + t_{is'j} \times CO_{2,is'}$$

[8] We also investigate our main results in a version of the model in which the carbon tax is instead paid in the origin country by producers. Results are similar and the main conclusions of the paper remain unchanged.

2.2 Demand

Consumers have Cobb-Douglas-CES preferences across sourcing origins for a given sector:

$$U_j = \prod_{s'} {U_{s'j}}^{\beta_{s'j}}$$

$$U_{s'j} = \left(\sum_i a_{is'}^{(1/\sigma_{s'})} q_{is'j}^{(\sigma_{s'}-1)/\sigma_{s'}} \right)^{\sigma_{s'}/(\sigma_{s'}-1)}$$

in which $a_{is'}$ is an origin-sector specific preference shifter, $\sigma_{s'}$ is a sector-specific elasticity of substitution, and $\beta_{s'j}$ is country j's expenditure share in sector s', such that $\sum_{s'} \beta_{s'j} = 1$.

2.3 Production

Markets are perfectly competitive. Production of good s in country j requires labor and intermediate inputs from all the sectors of the economy. These are combined in a Cobb-Douglas fashion with constant returns to scale. Denoting q_{js} the quantity of output s produced in j we have:

$$q_{js} = A_{js} \left(\frac{L_{js}}{\gamma_{j,Ls}} \right)^{\gamma_{j,Ls}} \prod_{s'} \left(\frac{m_{s'js}}{\gamma_{s'js}} \right)^{\gamma_{s'js}}$$

in which L_{js} is the amount of labor used in j to produce s; $m_{s'js}$ is the amount of intermediate input of sector s' used in j to produce s; $\gamma_{j,Ls}$ is the cost share of labor in production; and $\gamma_{s'js}$ is the cost share of input s' used in the production of s in country j, with $\gamma_{j,Ls} + \sum_{s'} \gamma_{s'js} = 1$. A_{js} is an exogenous productivity shifter.

Note that intermediate inputs can be sourced domestically or imported, so that $m_{s'js}$ is a CES aggregate of country i-specific varieties of the input:

$$m_{s'js} = \left(\sum_i b_{is's}^{(1/\eta_{s's})} m_{is'js}^{(\eta_{s's}-1)/\eta_{s's}} \right)^{\eta_{s's}/(\eta_{s's}-1)}$$

in which $b_{is's}$ is a preference shifter for variety i of product s' used in the production of s and $\eta_{s's}$ is the elasticity of substitution between origins of good s' used in the production of good s.

2.4 Equilibrium in Levels

Utility maximization subject to the budget constraint implies that each firm faces standard CES demands:

$$q_{is'j} = a_{is'}[p_{is'}\tau_{is'j}(1+t^e_{is'j})]^{-\sigma_{s'}} I_{s'j} \overset{c}{P}_{s'j}^{(\sigma_{s'}-1)} \tag{1}$$

in which $p_{is'}$ is the price of a good from sector s' produced in country i, $I_j = \sum_i q_{is'j}p_{is'j}(1+t^e_{is'j})$ is country j's income and $\overset{c}{P}_{s'j} = \left(\sum_i a_{is'}[p_{is'j}(1+t^e_{is'j})]^{(1-\sigma_{s'})}\right)^{\frac{1}{(1-\sigma_{s'})}}$ is a standard CES consumer price index.

Cost minimization subject to production technology constraints implies that:

$$m_{is'js} = b_{is's}[p_{is'}\tau_{is'j}(1+t^e_{is'j})]^{-\eta_{s's}} E_{s'js} \overset{\pi}{P}_{s'js}^{(\eta_{s's}-1)} \tag{2}$$

in which w_j is the wage in j, $E_{s'js} = \sum_i m_{is'js}p_{is'j}(1+t^e_{is'j})$ is the expenditure of sector s firms in country j with sector s' inputs and $\overset{\pi}{P}_{s'js} = \left(\sum_i b_{is's}[p_{is'j}(1+t^e_{is'j})]^{(1-\eta_{s's})}\right)^{\frac{1}{(1-\eta_{s's})}}$ is the appropriate index of intermediate goods. The price of the input bundle is a Cobb-Douglas aggregation of the wage rate and the price of intermediate inputs:

$$p_{is'} = \frac{(w_i)^{\gamma_{i,Ls'}}}{A_{is'}} \prod_k (\overset{\pi}{P}_{kis})^{\gamma_{kis}} \tag{3}$$

Market clearing implies that the consumer balance equalizes expenditure with final goods I_j to the wage bill plus revenues from carbon taxes obtained from the consumption of intermediates:

$$I_j = \sum_s w_j L_{js} + \sum_{i,s',s} p_{is'j} m_{is'js} t^e_{is'j} + D_j \tag{4}$$

in which D_j is an exogenous and fixed deficit for each country, with $\sum_j D_j = 0$.[9]

Market clearing also implies that in the producer balance expenditure with intermediate inputs and wages $E_{js} = \sum_{s'} E_{s'js}$ is equal to the revenue obtained from domestic and foreign sales:

[9]Notice that carbon taxes obtained from imports of final goods are absent from the expression (4) as they are both paid by consumers and rebated lump-sum to them.

$$E_{js} = \sum_i \left(p_{jsi} \left(q_{jsi} + \sum_{s'} m_{jsis'} \right) \right) \tag{5}$$

By summing (4) and (5) we obtain the country trade balance, where taxes cancel out because they are domestic:

$$\sum_{i,s'} p_{is'j} q_{is'j} + \sum_{i,s',s} p_{is'j} m_{is'js} = D_j + \sum_{i,s} \left(p_{jsi} \left(q_{jsi} + \sum_{s'} m_{jsis'} \right) \right) \tag{6}$$

Last, labor market clearing in each country implies that:

$$\sum_s \gamma_{j,Ls} \frac{E_{js}}{w_j} = L_j \tag{7}$$

We define an equilibrium under carbon taxes $\{t_{is'j}\}$ as a set $\{q_{is'j}, m_{is'js}, p_{is}, I_j, E_{js}, w_j\}$ that satisfies equilibrium conditions (1), (2), (3), (4) and (5) for all i, j, s' and s.

2.5 Equlibrium in changes

In order to take the model to the data, we use Dekle et al. (2007)'s "exact hat algebra", which is now standard in the literature. This involves re-writing variables as linear changes from the baseline. In what follows, a baseline version of a variable x is denoted by x^B. The proportional change is then given by $\tilde{x} = x/x^B$. Observe that this procedure has the advantage of eliminating the parameters that are hard to observe in the data, such as preference shifters $a_{is'}$ and $b_{is's}$, productivity shifters A_{js} and iceberg trade costs $\tau_{is'j}$, thus simplifying the quantitative analysis. It also implies that the model perfectly matches the global pattern of trade and production described by the data in the baseline.

Following this procedure, changes in the demand for final goods, the demand for inputs, price indexes, and ex-factory prices are given by:

$$\widetilde{q}_{is'j} = \widetilde{I}_{s'j} [\widetilde{p}_{is'} (1 + t^e_{is'j})]^{-\sigma_{s'}} \ \overset{c}{\widetilde{P}}_{s'j}^{(\sigma_{s'}-1)} \tag{8}$$

$$\overset{c}{\widetilde{P}}_{s'j} = \left(\sum_i [\widetilde{p}_{is'} (1 + t^e_{is'j})]^{(1-\sigma_{s'})} \left(\frac{q^B_{is'j} p^B_{is'j}}{I^B_{s'j}} \right) \right)^{\frac{1}{(1-\sigma_{s'})}} \tag{9}$$

$$\widetilde{m}_{is'js} = \widetilde{E}_{s'js}[\widetilde{p}_{is'}(1+t^e_{is'j})]^{-\eta_{s's}} \; \widetilde{P}^{\pi \; (\eta_{s's}-1)}_{s'js} \tag{10}$$

$$\widetilde{P}^{\pi}_{s'js} = \left(\sum_i [\widetilde{p}_{is'j}(1+t^e_{is'j})]^{(1-\eta_{s's})} \left(\frac{m^B_{is'j} p^B_{is'js}}{E^B_{s'js}} \right) \right)^{\frac{1}{(1-\eta_{s's})}} \tag{11}$$

$$\widetilde{p}_{js} = \widetilde{w}_j^{\gamma_{j,Ls}} \prod_{s'} \widetilde{P}^{\pi \; \gamma_{s'js}}_{s'js} \tag{12}$$

Changes in the market clearing conditions are given by:

$$\widetilde{I}_{s'j} = \sum_s \widetilde{w}_j \widetilde{L}_{js}(w^B_j L^B_{js}) + \sum_{i,s',s} \widetilde{p}_{is'} \widetilde{m}_{ijs's} t^e_{ijs'}(p^B_{is'j} m^B_{is'js}) + D^B_j \tag{13}$$

$$\widetilde{E}_{js} = \sum_i \left(\widetilde{p}_{js} \widetilde{q}_{jsi}(p^B_{jsi} q^B_{jsi}) + \sum_{s'} \widetilde{p}_{js} \widetilde{m}_{jsis'}(p^B_{jsi} m^B_{jsis'}) \right) \tag{14}$$

$$\sum_s \frac{\widetilde{E}_{js}}{\widetilde{w}_j} L^B_{js} = L_j \tag{15}$$

In Appendix B, we show that the model expressed in changes can be reduced to a parsimonious $N \times S$ system that we use to explore the consequences of climate policies and international transfers that aim at delivering climate justice.

2.6 International Transfers

A main goal of our analysis is to quantify international monetary transfers that could be used to balance the costs involved in the widespread adoption of climate policies. In this subsection, we explain how we formally introduce such transfers in the theoretical framework outlined above and detail how we design the quantification routine to account for the main concerns of the principle of Common but Differentiated Responsibilities.

First, notice that domestic real income is given by total expenditure with final goods deflated by the domestic consumer price index. Hence, the associated real income changes are defined by:

$$\tilde{W}_j = \frac{\widetilde{I}_j}{\Pi_{s'} \widetilde{P}^{\beta_{s'j}}_{s'j}} \tag{16}$$

We use this measure of real income to solve for two types of contribution schemes. First, an "equal-cost" scenario, which makes sure that the adoption of a global carbon tax leads to uniform real income changes across countries irrespective of their present-day relative contribution to total GHG emissions. Second, a "historic polluter pays" transfer scheme ensures that the real income costs of climate policies are proportional to the country's cumulative GHG emissions since the onset of the Industrial Revolution. Our first scenario would thus be a simple benchmark for perfect equality in climate action, whereas our second scenario aims at applying the CBDR principle. Next, we provide more details on how we formally model both types of schemes.

Equal Cost Transfers We define international transfers as an exogenous income source at the country level, T_j. In the "equal cost transfer" case, we compute transfers paid or received such that the real income changes induced by the carbon tax are equalized across countries. Formally, we want to solve the general equilibrium such that:

$$\widetilde{W}_j = \widetilde{W} \tag{R1}$$

$$\sum_j T_j = 0 \tag{R2}$$

Restriction (R1) implies that cross-country real income changes that results from the adoption of a global carbon tax are the same. Restriction (R2) is a zero-sum condition that makes sure that transfers are balanced. By rewriting R1 we can explicitly solve for each country's equal cost transfer:

$$T_j = H_j \frac{\sum_j G_j}{\sum_j H_j} - G_j \tag{17}$$

where $H_j = \left(I_j^B \times \Pi_{s'} \widetilde{P}_{s'j}^{\beta_{s'j}} \right)$ and $G_j = \sum_s w_j L_{sj} + \sum_{is'} p_{is'j} q_{is'j} t^e_{is'j} + \sum_{is's} p_{is'j} m_{is'js} t^e_{is'j} + D_j$. To back out T_j in this case, we add (17) as a fixed point to the algorithm described in Appendix B together with condition (R2).

Historic polluter-pays transfer For this type of contribution scheme, we want to compute country-level international transfers T_j that are proportional to historical emissions of GHG in each country. We achieve this by solving the general equilibrium such that:

$$(\widetilde{W}_j - 1)W_j^B = \Gamma \left[\frac{Z_j}{\sum_j Z_j} \right] \tag{R3}$$

$$\sum_j T_j = 0 \tag{R4}$$

where W_j^B is a measure of real income in the baseline, Z_j are historical greenhouse gas emissions in country j and Γ is an endogenous proportionality factor. Restriction (R3) implies that changes in real income are proportional to the share of historical emissions in each country. Restriction (R4) is a zero-sum condition as before. Again, we can use the two conditions to explicitly solve for transfers T_j:

$$T_j = H_j - G_j + \Omega_j^B H_j \frac{\sum_j (G_j - H_j)}{\sum_j \Omega_j^B H_j} \tag{18}$$

where G_j and H_j are defined as before and $\Omega_j^B = \left[\frac{Z_j}{\sum_j Z_j} \right] \frac{1}{C_j^B}$. Notice that the zero-sum condition determines the proportionality factor:

$$\Gamma = \frac{\sum_j (G_j - H_j)}{\sum_j \Omega_j^B H_j} \tag{19}$$

To back out transfers in this case, we add expressions (18) and (19) as a fixed point to the algorithm described in the Appendix B.[10]

3 Data

This section describes the data sources, the data treatment, and the calibration of the parameters.

3.1 Data sources

Data on production, consumption, and trade flows come from the OECD Inter-Country Input-Output (ICIO) tables (OECD, 2023). The ICIO tables report data on intermediate input use, final demand, consumption expenditure of various accounting units, value-added and gross output in 45 distinct sec-

[10] Since we cannot observe sector-level price indexes in the data, we use consumption data in the baseline to solve for transfers in the "polluter pays" scheme. As shown in Figure 18, this procedure leads as intended to a counterfactual equilibrium in which carbon taxes and transfers imply a perfect correlation between changes in real income and the historical cross-country pattern of GHG emissions.

tors for 67 countries, including a Rest of the World aggregate, from 1995 to 2018.

Data on greenhouse gas emissions in CO_2 equivalents are constructed by combining three different datasets: the OECD Carbon Dioxide Emissions Embodied in International Trade dataset (TECO2) (OECD, 2021), the FAOSTAT Domain Emission Totals (FAO, 2023), and the European Commission's Emissions Database for Global Atmospheric Research (EDGAR) (European Commission, 2023). The TECO2 dataset is constructed by combining the ICIO tables with the International Energy Agency's database on Greenhouse Gas Emissions from Energy (IEA, 2024). It provides CO_2 emissions from fuel combustion in production of the 45 sectors and 67 countries of the ICIO for the period 1995 to 2018. To extend the emissions coverage and include non-energy-related emissions, we make use of the CO_2, CH_4 and N_2O emissions from the two remaining datasets: we use the FAO data for emissions from agriculture, forestry, and land-use,[11] and the EDGAR database[12] for emissions from industrial processes and product use as well as fugitive emissions. We describe how we combine the datasets in detail in the Appendix under section A.

Figure 1 shows the evolution of the different types of greenhouse gas emissions that we account for in the data from 1995 to 2018. The y-axis is measured in Gigatons of CO_2e. Carbon dioxide (CO_2) is the main contributor to greenhouse gas emissions, while methane (CH_4) and nitrous oxide (N_2O) are non-negligible components as well. The striped part of emissions refers to data that exists, but that we cannot unambiguously map to our sector classification. Additionally, we do not consider F-Gas emissions. All in all, we cover around 93% of total emissions in 2018. Figure 2 shows the evolution of emissions according to their source, again in Gigatons of CO_2e. The brown areas on the bottom of the graph (energy, industries, transports) stem from the TECO2 dataset and relate to fuel combustion. The agricultural and forestry emissions stem from the FAO dataset, while the fugitive emissions and industrial process emissions stem form EDGAR. This graph shows why including methane and nitrous oxide emissions is important: Emissions related to agriculture are a large share of the overall emissions. If we only considered emissions from fuel combustion, the impact of the agricultural sector to greenhouse gas emissions would be neglected.

[11]The FAO dataset contains estimates of GHG emissions computed at Tier 1 following the IPCC Guidelines for National GHG Inventories. It includes estimates of 16 emission categories for 191 countries from 1961 to 2019.

[12]The EDGAR dataset reports among other substances direct GHG calculations of 35 IPCC emissions categories for 232 countries from 1970 until 2018.

Figure 1: Emissions by gas

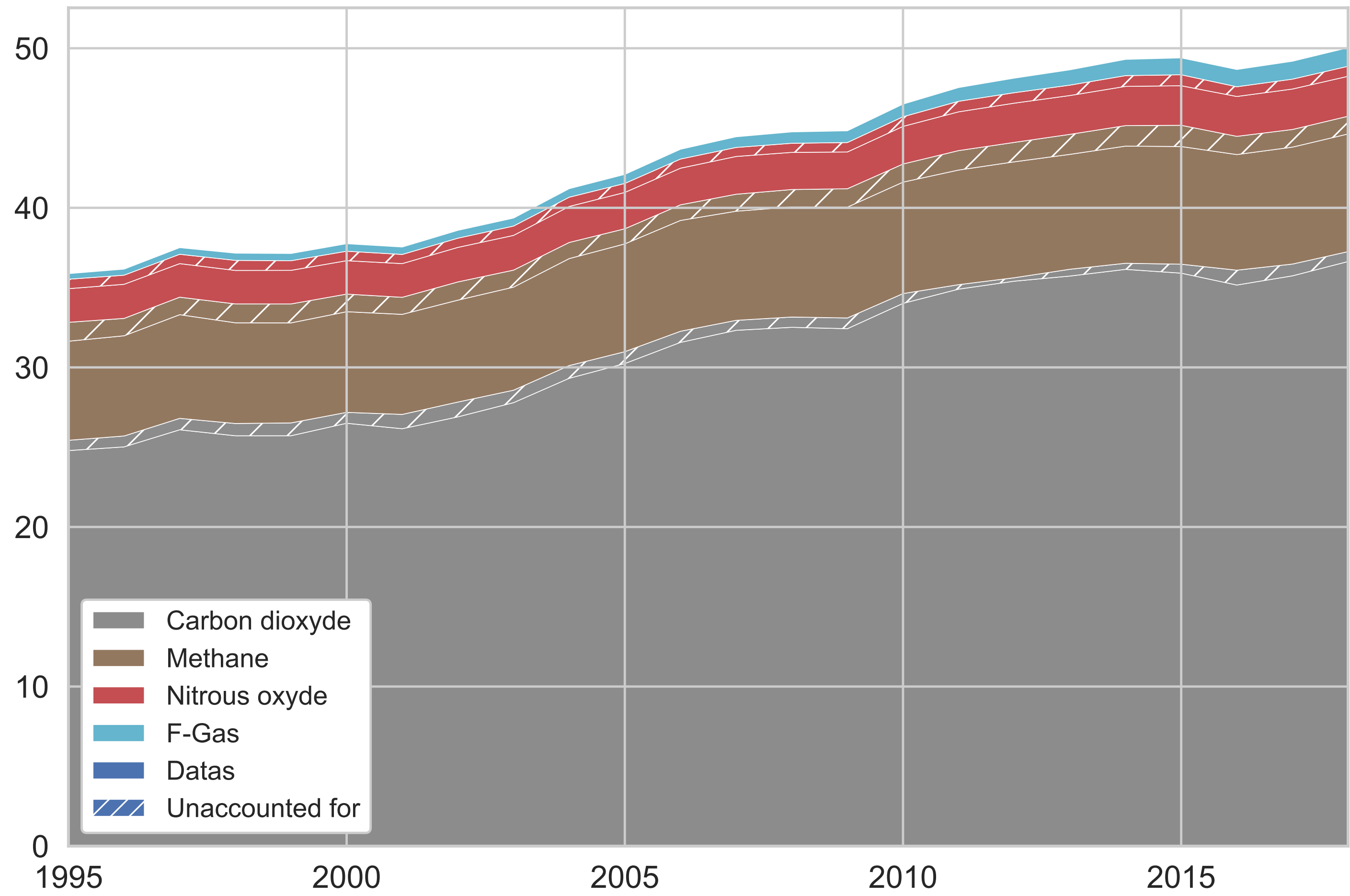
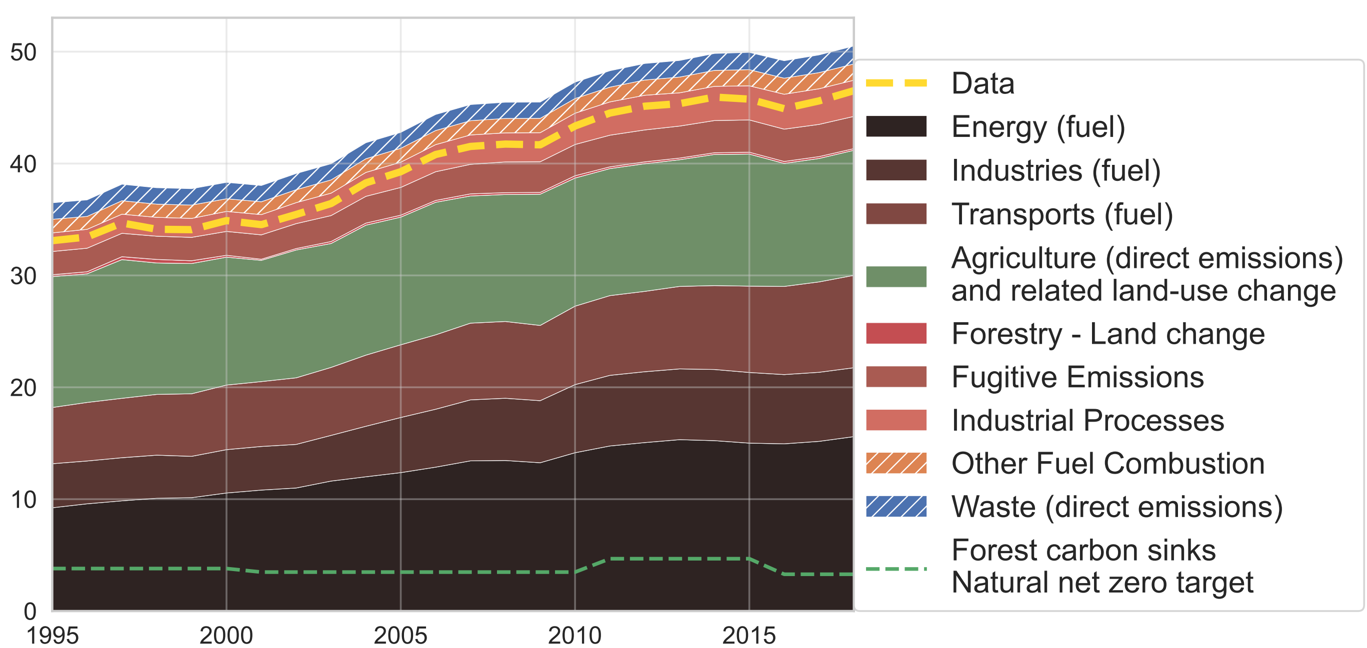


Figure 2: Emissions by source



Now we turn to the emissions by sector in Figure 3. The y-axis shows all sectors in the final data set, where we group all the services sectors for readability. The x-axis shows the emissions intensity of a sector in tons of CO_2e across countries. There are two main takeaways: Looking at the y-axis, there is large variation in emissions across sectors. Water and air transport, the agricultural sector, the mining sectors, energy, and raw materials are among the most polluting sectors. Looking at the x-axis, there is a large variation in emission intensities across different countries. Plotting the density of the emissions intensity in % deviation from the sectoral mean in Figure 4, we can observe a positive skew. That means that there are a few countries that have a much higher emission intensity than the average country in a given sector.

Figure 3: Sectoral emissions

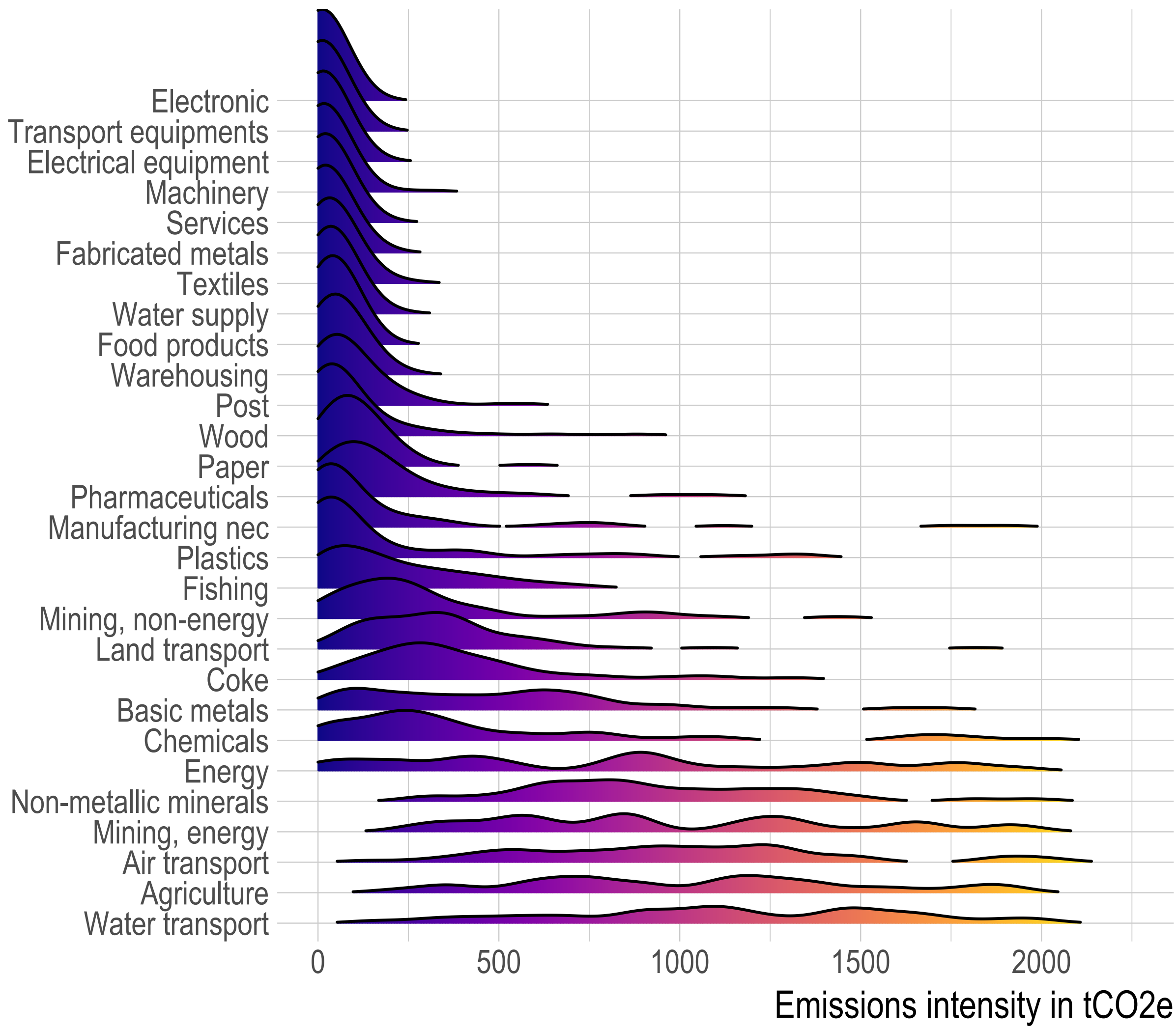


Figure 4: Density of emissions intensity

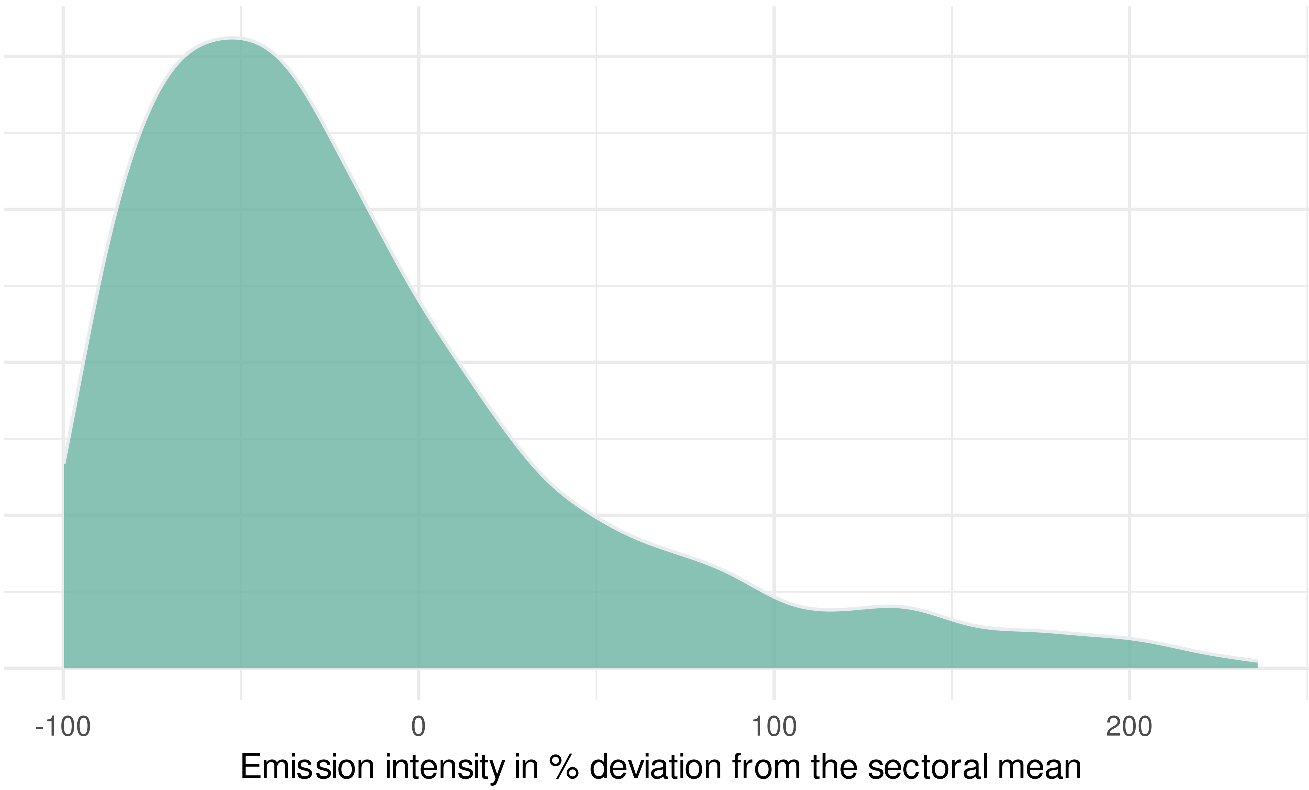
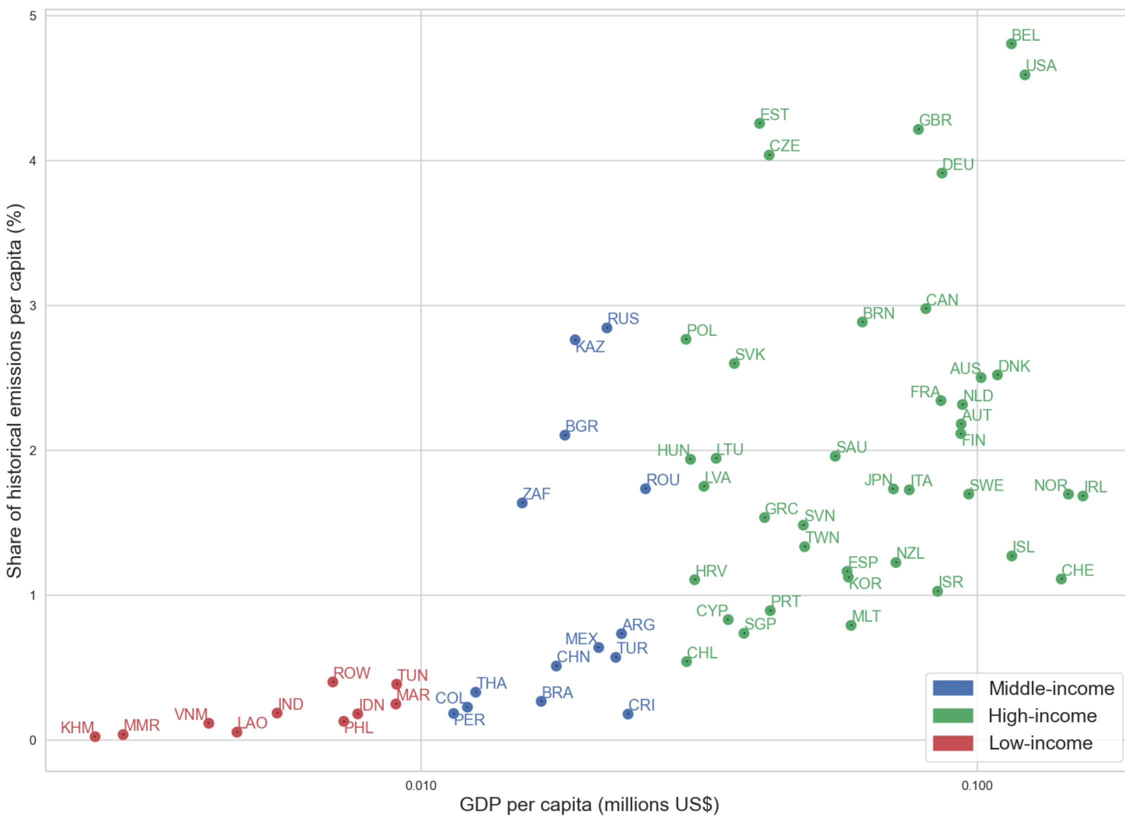


Figure 5 shows the historical cumulative emissions per capita for each country, based on data from Ritchie (2019). The countries with the largest GDP per capita are also responsible for the largest share of historical emissions per capita. Low-income countries have historically contributed very little to emissions.

Figure 5: Historical Emissions



3.2 Calibration

There are three parameters in the model that we need to calibrate. All of them are calibrated internally, using the year 2018.

- Elasticity of substitution across origins in consumption and in intermediate input use:
  We assume $\sigma_{s'} = \eta_{s's} = \eta_{s'}$ as is common in the literature (Caliendo and Parro, 2015). We estimate the elasticities along the lines of Caliendo and Parro (2015). As a robustness check, we provide two alternative specifications for the elasticities. First, we estimate them according to Fontagné et al. (2022). Second, we use the elasticities provided by Fontagné et al. (2022) and map them to our industry classification. We provide more details on elasticities in Appendix C. Our results are robust to using different elasticities.

- Cobb-Douglas utility parameters (expenditure shares) $\beta_{s'j}$:

  These are calibrated in the data as the ratio of consumption expenditure over total expenditures.

- Cobb-Doublas production function parameters (expenditure shares) $\gamma_{j,Ls}$ and $\gamma_{s'js}$:

  These are calibrated in the data as the ratio of intermediate input expenditures over gross output.

- Cobb-Doublas production function parameters (labor share) $\gamma_{j,Ls}$:

  This is calibrated in the data as the value added in gross output.

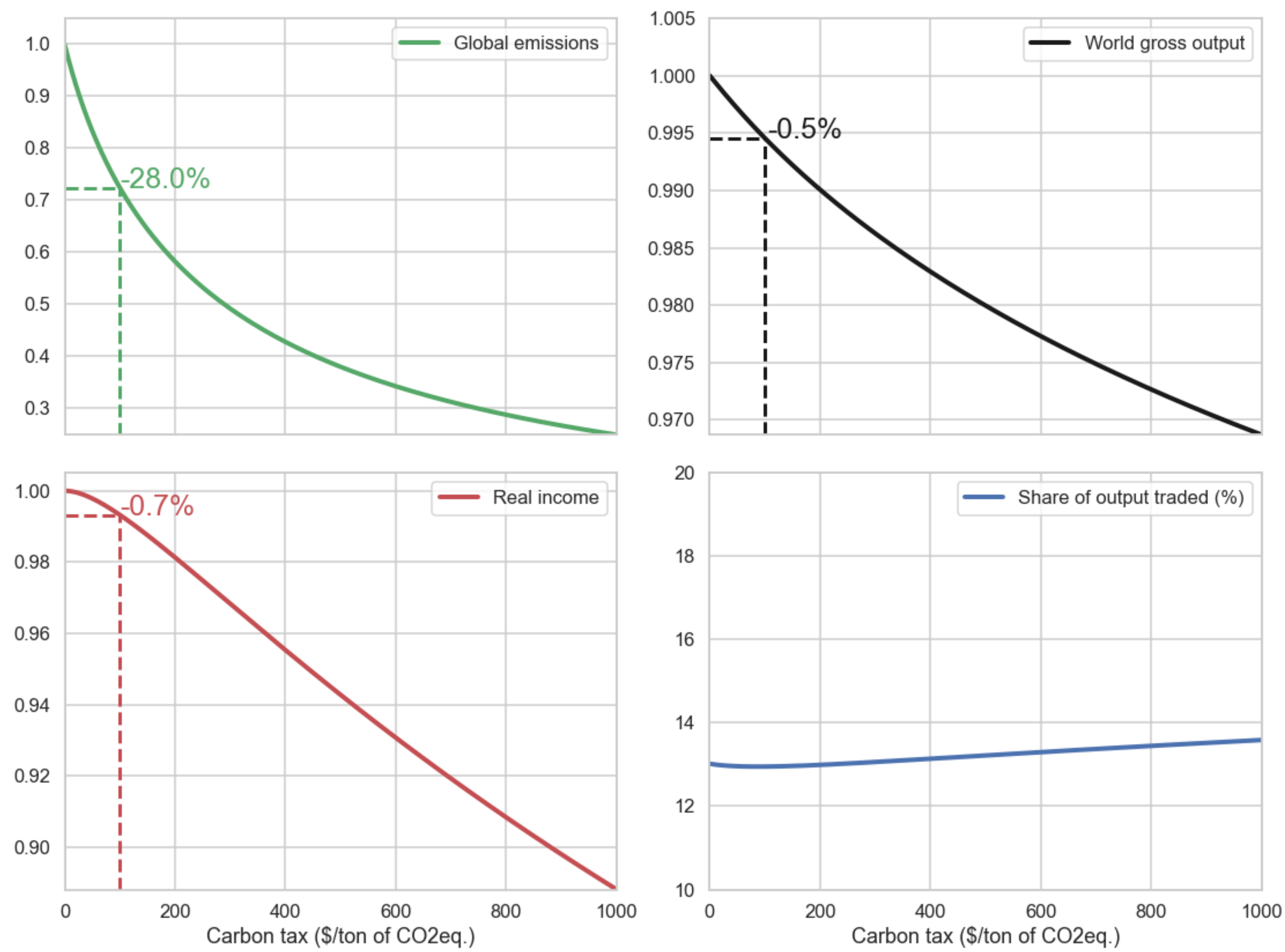
4 Results

4.1 Carbon taxes

This section presents the results of implementing carbon taxes in the model. We will mostly focus on the effect of a 100 USD/tCO_2e carbon tax.

Figure 6 shows the macro effects of carbon taxes. The x-axis shows different levels of taxes and the y-axis shows the change in outcomes compared to the baseline without taxes. The upper left panel depicts global emissions. For smaller levels of carbon taxes, the decrease in emissions is larger. The bottom left panel shows real income which will decrease with higher levels of carbon taxes. For very large levels of carbon taxes, emissions decrease a lot, but this comes at a large economic cost as real income decreases linearly. World gross output in the upper right panel decreases as well as a response to higher carbon taxes. Interestingly, the share of output traded in the bottom right panel stays relatively constant, even for high levels of taxes. This suggests that there is still a role for international trade, even at very high levels of taxes. Focusing on a carbon tax of 100 USD/tCO_2e, a carbon tax seems to be very effective. We obtain a decrease in emissions of 28% for a decrease in real incomes of 0.7% and a decrease in world gross output of 0.5%.

Figure 6: Macro effects of carbon taxes



4.1.1 Country effects

The previous Figure on the macro effects (Figure 6) refers to the average across countries and masks a large heterogeneity. Figure 7 shows the real income change for each country and their GDP per capita. The graph reveals that most low- and middle-income countries experience a strong decrease in real incomes, while most high-income countries even experience a real income gain. This result is striking: There is evidence that low- and middle-income countries are hurt the most by climate change[13]. We show that implementing a Pigouvian tax which is often considered the most effective policy to combat climate change also hurts low- and middle-income countries the most, as they would experience the largest decreases in real income.

[13]The vulnerability of developing countries to the effects of climate change has been as demonstrated repeatedly by the Intergovernmental Panel on Climate Change (IPCC) in the report of their second working group (Adler et al., 2022).

Figure 7: Real income changes

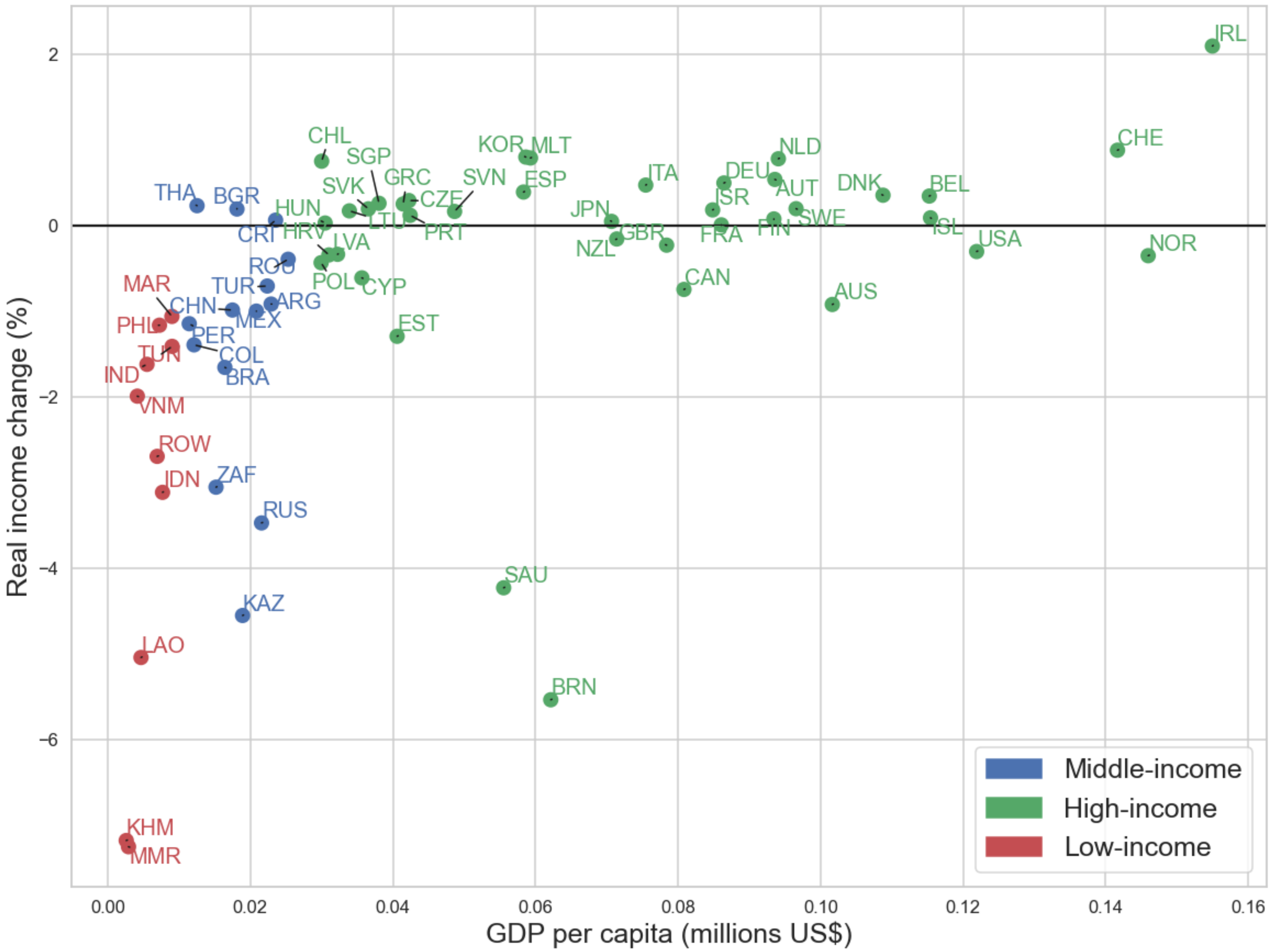
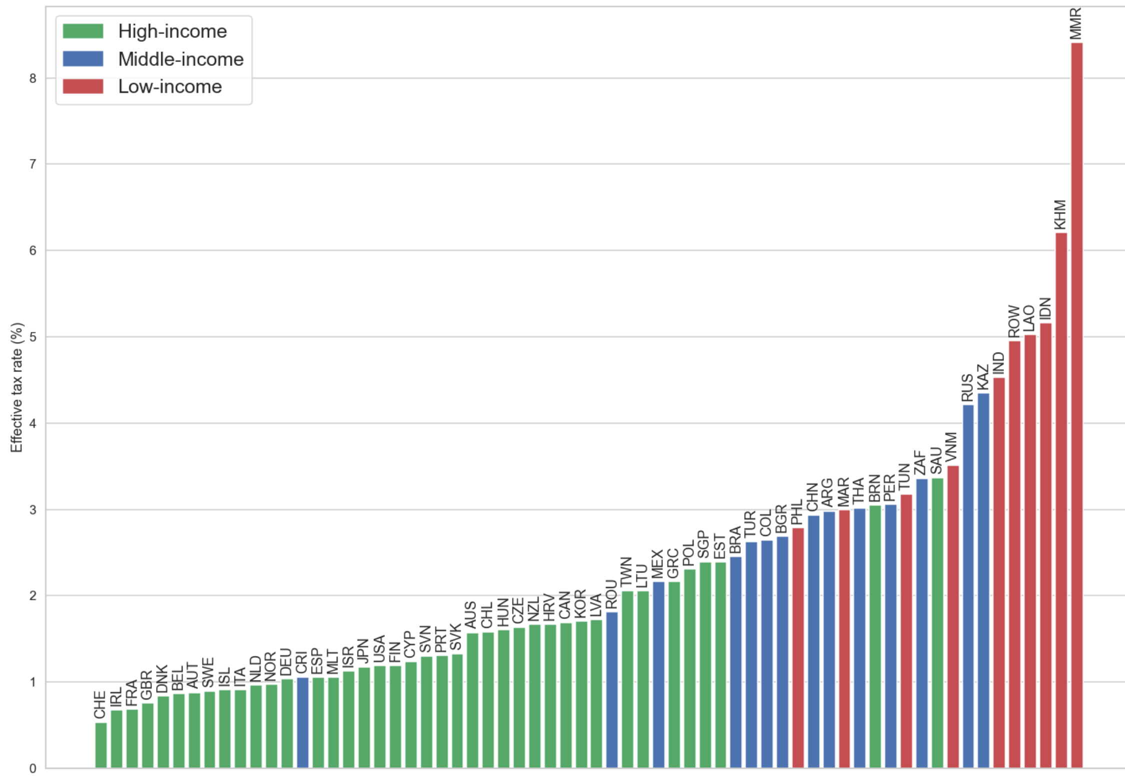


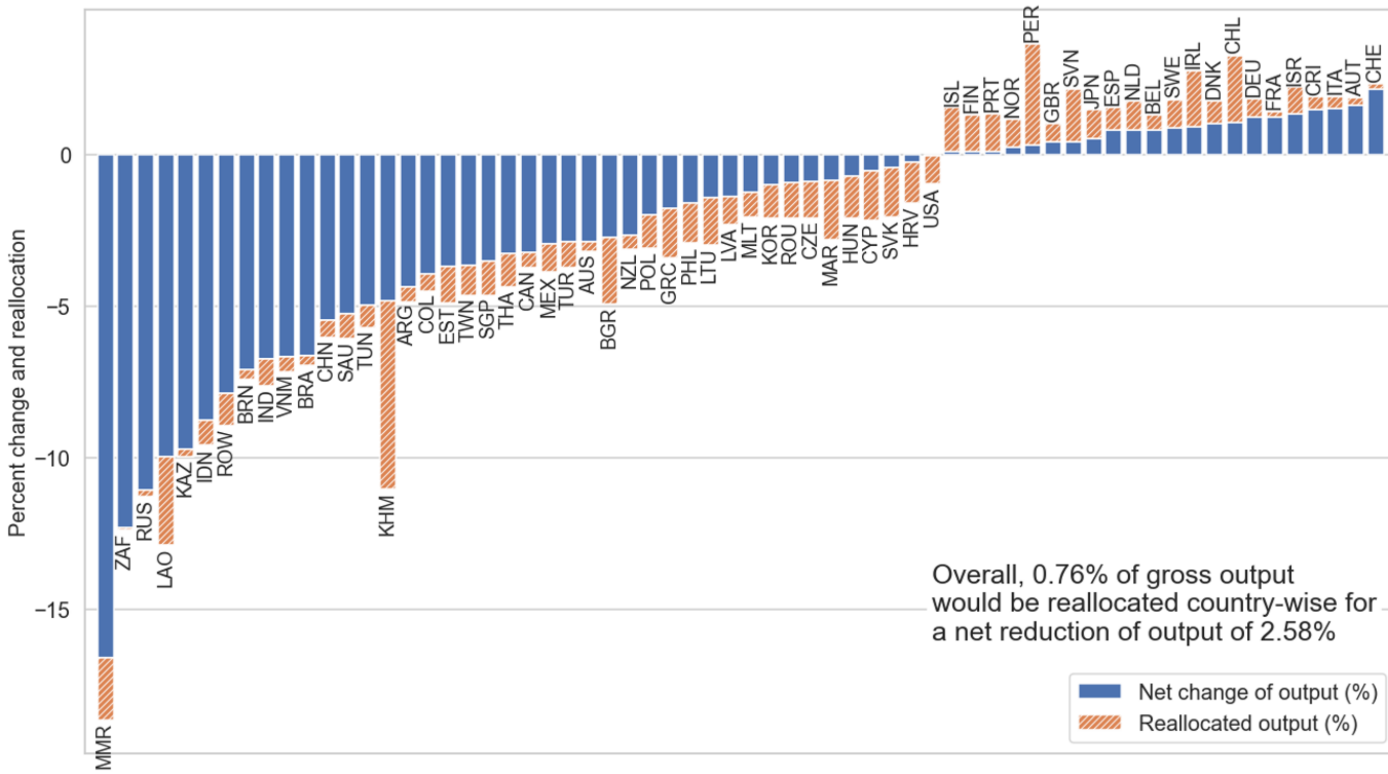
Figure 8 shows the effective tax rate, which we calculate as the total tax paid by the producers and consumers in a country divided by the total expenditure of a country. It shows that most high-income countries pay tax rates of around 1-2%, while low-income countries pay up to 8%.

Figure 8: Effective tax rate



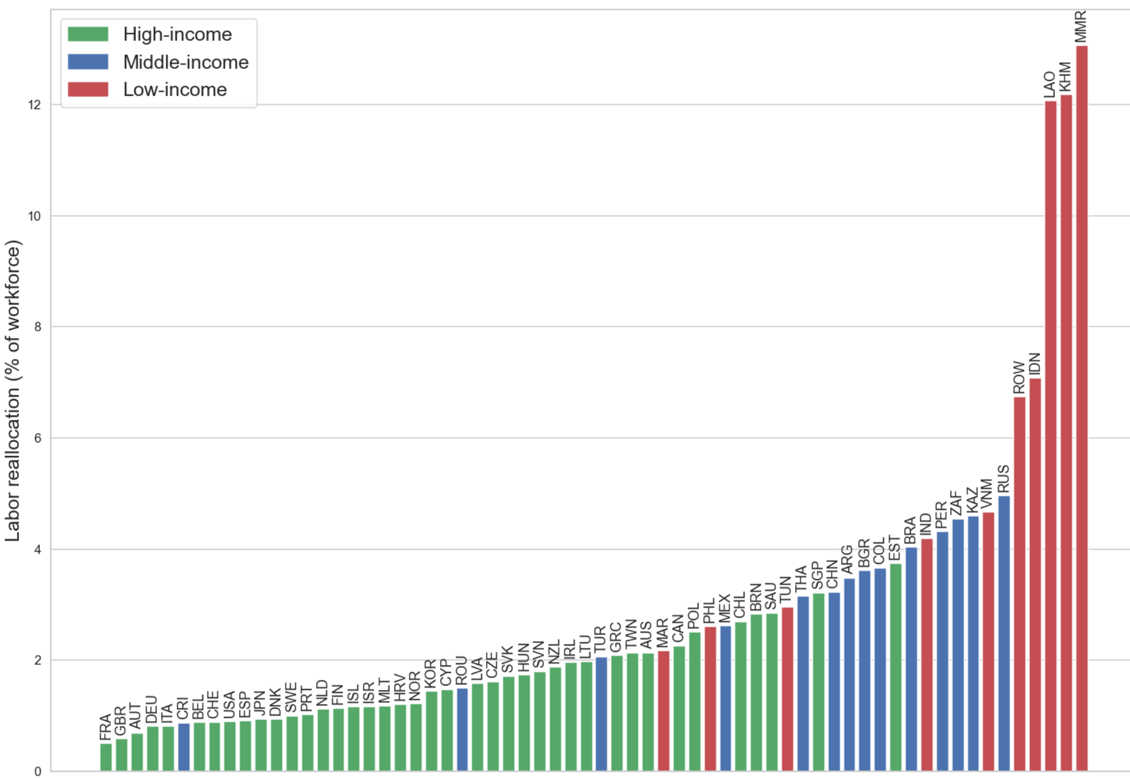
There are two ways in which we investigate the impact of the tax on different countries. First, we look at the reallocation of economic output across different countries. Second, we investigate the reallocation of labor. For the first exercise, Figure 9 shows the net change of output together with the reallocated output in percent. The sum of the two bars represents the total output decrease in all sectors in a country, the hatched orange bar represents the total output increase in all sectors. Thus, the blue bar is the net change in output and the hatched orange bar is the reallocated output. The low- and middle-income countries not only experience the largest decrease in net output, but they also exhibit a larger reallocation of their output. We find a decrease in gross output for most of the low- and middle-income countries in our sample, and net zero changes or net gains for high-income economies. These reallocation effects are large, in particular for European countries, and non-agricultural Latin American countries (Chile, Peru). Large reallocation effects reveal that low- and middle-income countries' sectoral mix is less effective in terms of environmental comparative advantage (Le Moigne et al., 2024), so a carbon tax will impose a larger adjustment for these countries not only in terms of income but also in terms of resources.

Figure 9: Country reallocation



For the second exercise, we investigate the reallocation of labor. Figure 10 shows the percentage of the workforce that has to move to a different sector as a response to the carbon tax. Since labor is immobile across countries, each country will have the same amount of workers in the new equilibrium. These workers might have to work in different sectors, though. Here again, low- and middle-income countries experience the largest reallocation of their workforce.

Figure 10: Labor reallocation



4.1.2 Sectoral effects

Implementing carbon taxes in our model will change the pattern of production and trade. We illustrate this in the next set of graphs, where we depict changes in production and trade flows across countries for specific sectors. The size of each country node represents the total output volumes traded (exports) in 2018. The color of the nodes represents the change in exports relative to the 2018 baseline and relative to the median decline. This latter precision is important to understand the graph: overall the model prescribes a decline in production and trade, so that most trade flows decline. The comparison to the median (in white) allows us to identify countries whose exports increase or decrease less than the median (in green) from countries whose exports are relatively more affected by the tax (in red). The size of the edge (arrow in between country pairs) represents the volumes of trade from a given exporter (indicated by a nodule) to a given importer in the data in 2018. The color of the edge represents the change in export volumes relative to the baseline and relative to the median.

Figure 11 shows the changes in trade patterns for all sectors. Overall, the high-income countries (US, Europe, and Japan, for example) will increase trade relatively to the median change in trade patterns as a response to the carbon tax, while low- and middle-income countries (China for example) will decrease trade. This general trend might be different for different subsectors. Figure 12 shows the trade patterns for the energy sector. Here, the US should export less in total and export less to Canada specifically, while Canada should increase production and export to the US. China has relatively dirty energy production and should therefore decrease its exports. In Figure 13 however, China is relatively green and should continue exporting agricultural products. There is a strongly red arrow from Brazil to China. Given that Brazil has relatively high emissions intensities, it should decrease its exports to China. In a fourth example from the basic metals sector in Figure 14, Chile and Peru are relatively green and should thus increase their exports. All in all, these figures show that while low- and middle-income countries do suffer the most from climate policy, there are certain subsectors where some low- and middle-income countries gain.

Figure 11: Micro effects of carbon taxes: All sectors

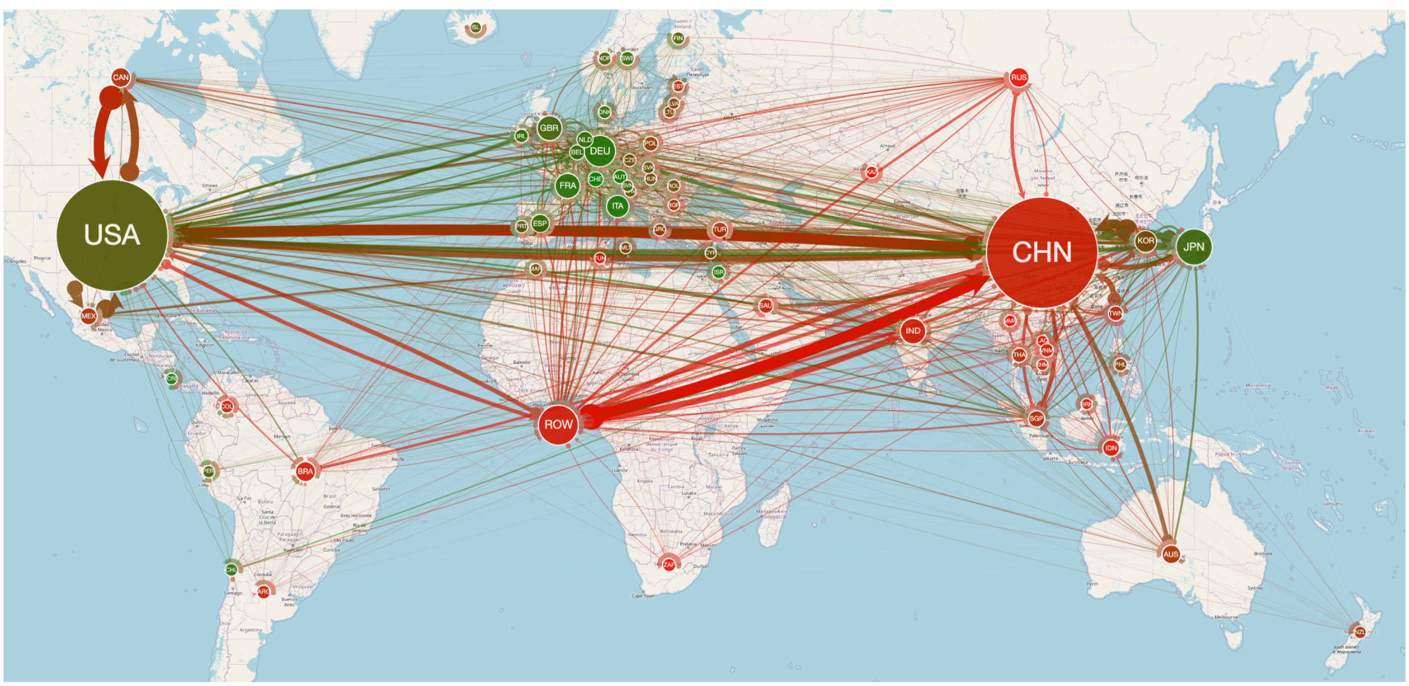


Figure 12: Micro effects of carbon taxes: Energy sector

Figure 13: Micro effects of carbon taxes: Agricultural sector

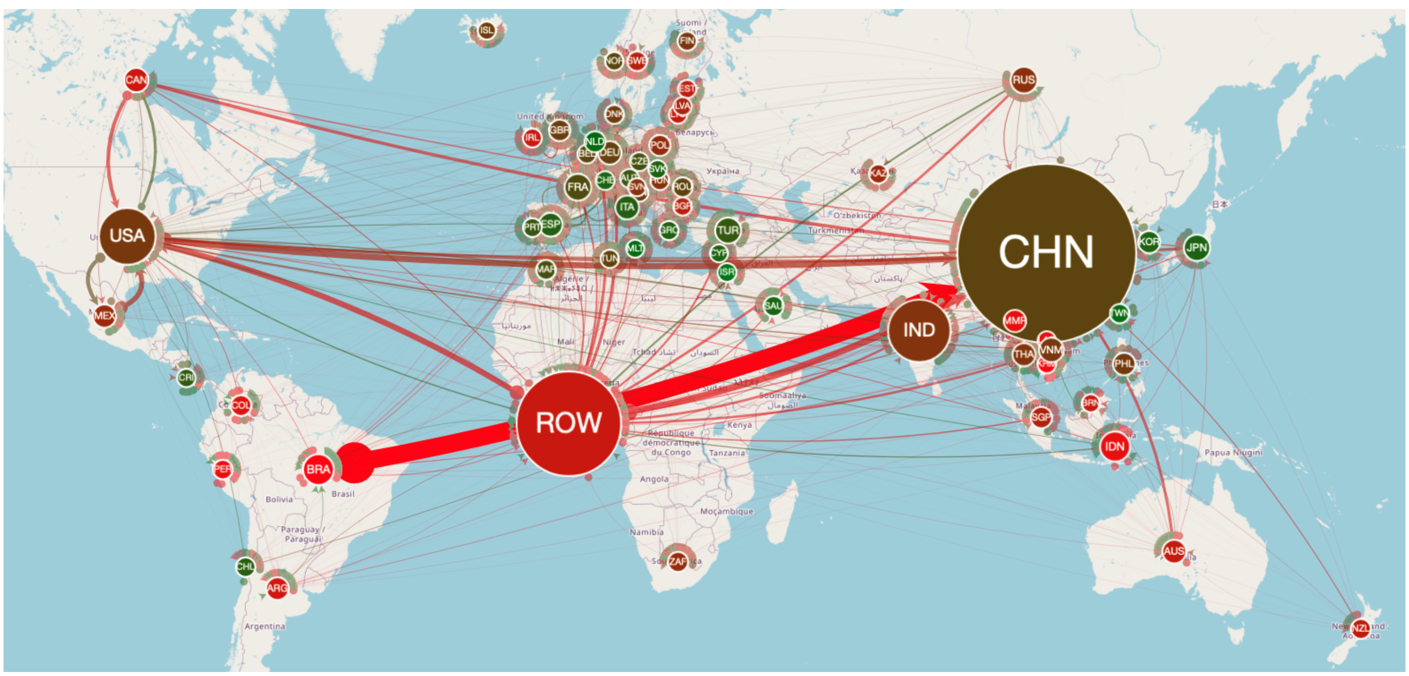
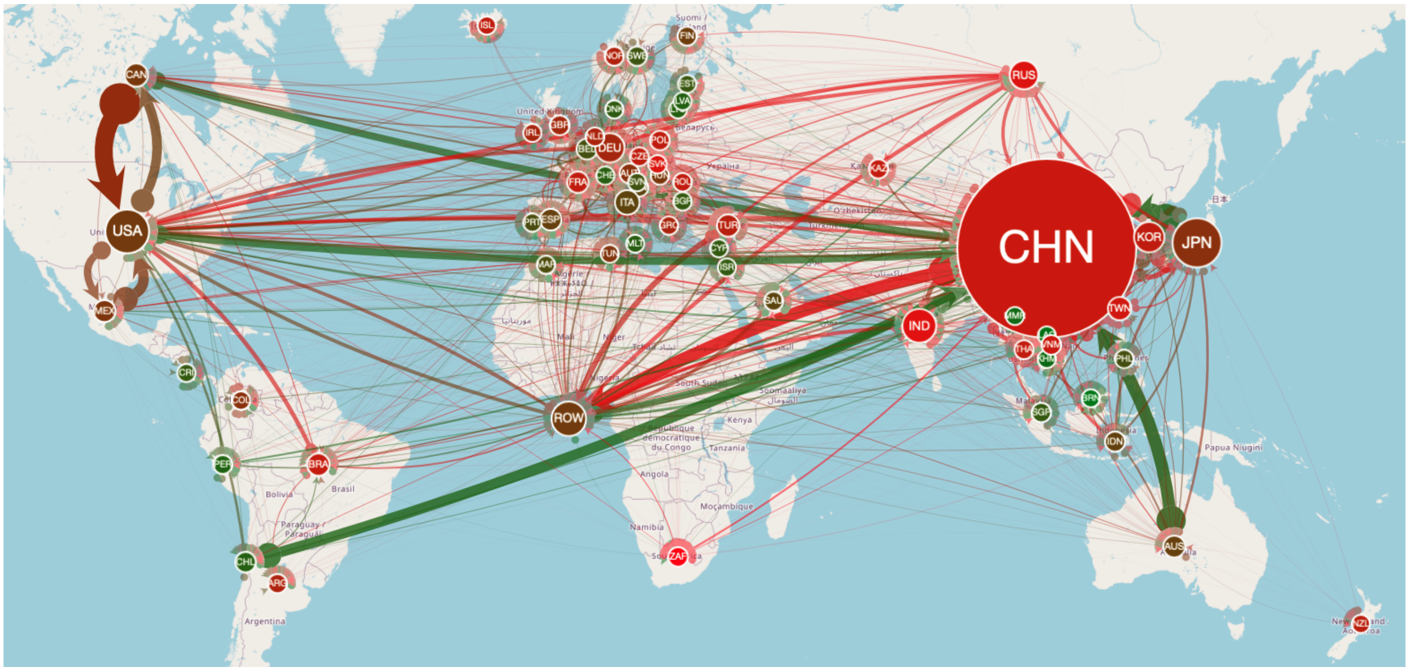
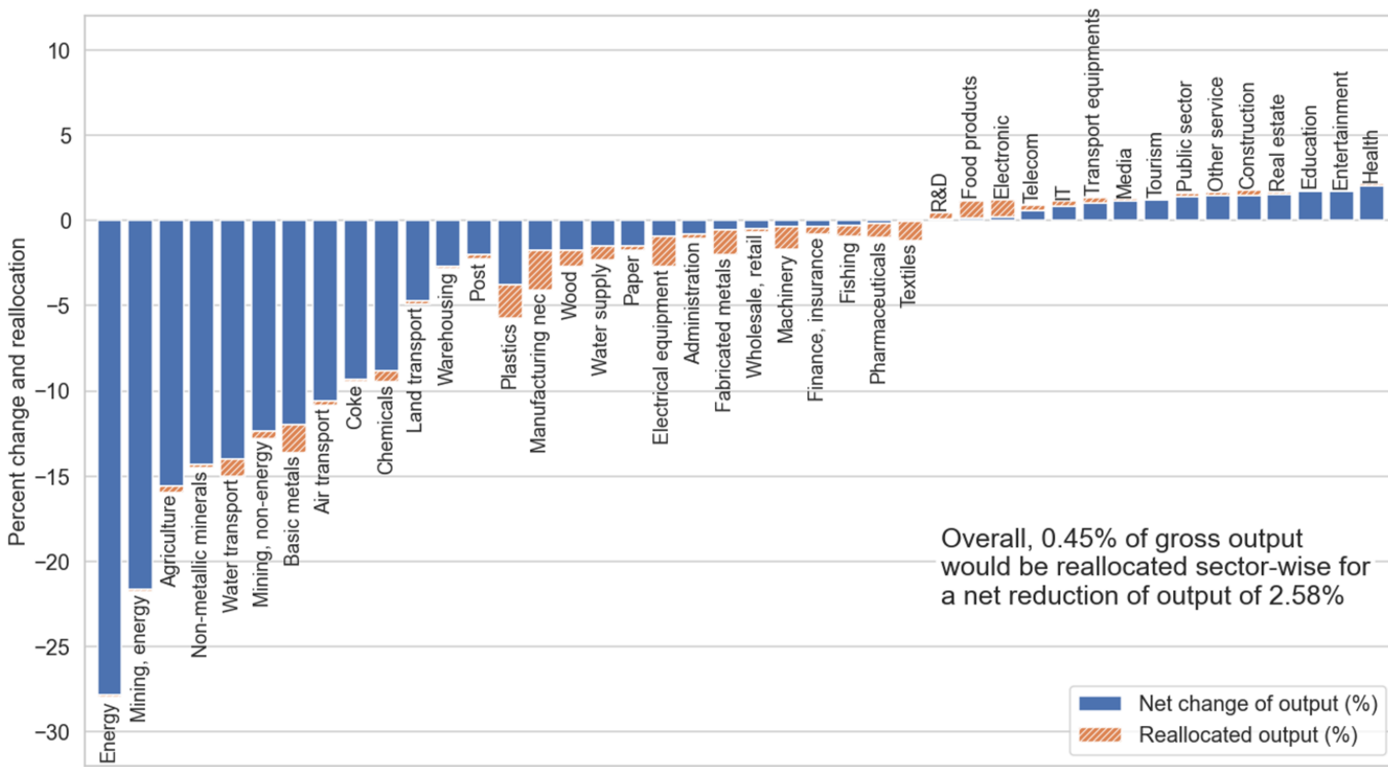


Figure 14: Micro effects of carbon taxes: Basic metals sector



Production can be reallocated across countries for a specific sector as seen in the previous graphs. Figure 15 shows how much of production is reallocated across countries for each sector. For each sector, the bars represent the percent change in a sector's gross output (across all producing countries) between the realized data in 2018 and the economy with a USD100/tCO_2e carbon tax. The filled blue bars represent the net change in output, whereas the hatched orange sections represent how much of a sector's output is produced in an origin different than previously. Unsurprisingly, the most polluting sectors (energy, agriculture, mining) experience the largest decrease in output. The services sectors instead show an increase in output. While water transport and air transport were among the most polluting sectors looking at their emissions intensity in Figure 3, these sectors do not experience the largest decrease in production. This is a feature of our general equilibrium model. In a partial equilibrium world, we would expect more polluting sectors to show a larger decrease in emissions. In our setting, we will have larger decreases in sectors that are relatively high up in the supply chain, as that will have trickle-down effects on the entire economy. These net effects hide potential substantial reallocations across countries within sectors, that are represented by the hatched bars. This reallocation effect or "green sourcing effect" can be quite large (Le Moigne et al., 2024), and sometimes even larger than the resulting net change. That means that in a given sector, the amount of production simply displaced from a dirty origin to a cleaner one is higher than the number of production capacities destroyed (in the case of a negative change) or created (in the case of a positive change). This phenomenon occurs in a wide range of sectors, from manufacturing equipment to fishing and food products to R&D.

Figure 15: Production reallocation



4.2 Transfers

In this section, we explore international transfer schemes aimed at delivering climate justice. Recall that transfers are needed because the costs associated with the implementation of climate change mitigation policies are disproportionately borne by developing countries. As we show next, moderate monetary transfers across countries can remedy this fact.

4.2.1 Equal Cost Transfers

Our first scenario is an "equal-costs" type of transfer, in which the goal is to perfectly equalize the real income costs of climate action. While this scenario does not implement the CBDR principle, as it does not account for differentiated responsibilities, it does ensure that at least poor countries do not bear the bulk of the economic costs.

Results show that the overall impact of the global common carbon tax paired with monetary transfers is de facto smoother than without transfers: the reduction of global emissions achieved is the same

(–28%) for identical aggregated real income costs (–0.7%). In addition, the gross-output decline is lower (–2.1% compared with –2.6% previously). Figure 16 shows the mechanism behind these results: changes in real income are all negative, lower than 1% and equally borne by all countries irrespective of their relative contribution to the climate crisis.

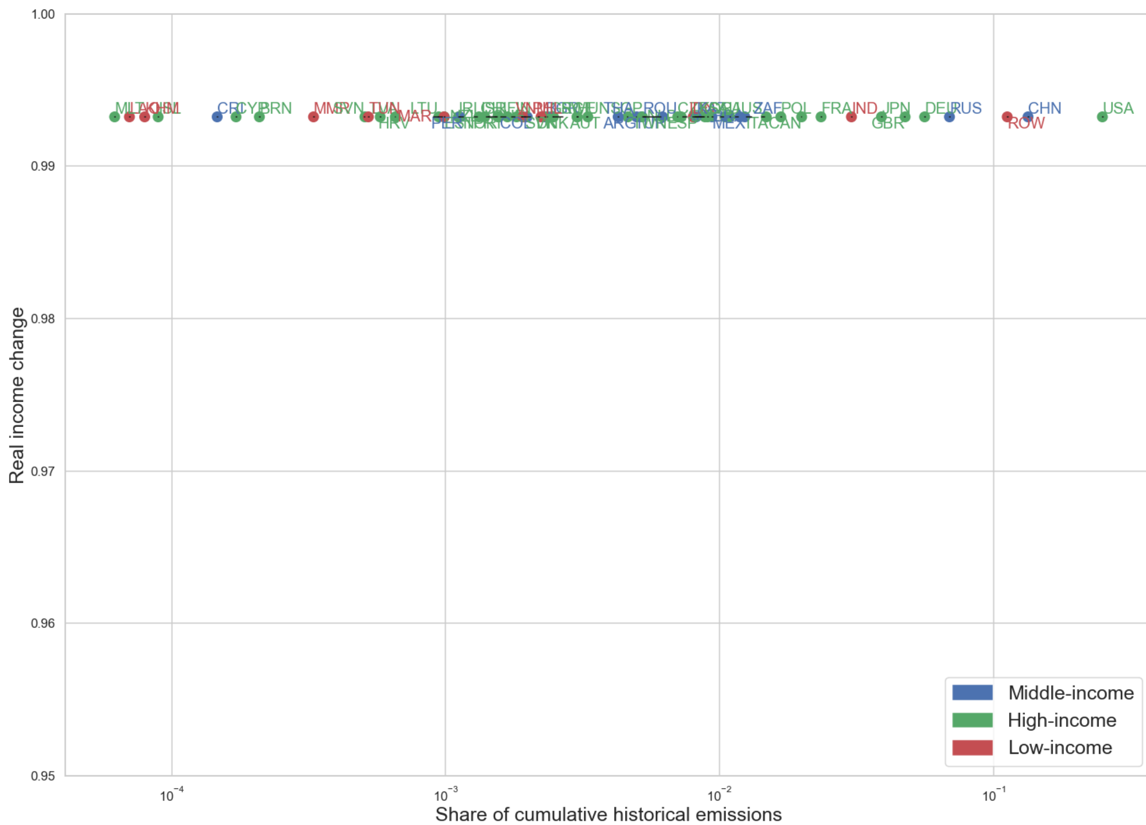
To equally split the costs of the carbon tax, fair transfers need to allocate resources according to countries' income level. This can be seen in Figure 17, which displays per capita transfers (in dollars) for all countries in the sample. A negative transfer represents an international side payment, while a positive one is an additional income source. Notice that with the exception of the two outliers that are Bahrain and Saudi Arabia,[14] The figure reveals that high-income countries in general have to pay a monetary transfer to low- and middle-income countries in order to equalize the economic cost of a global carbon tax. The largest payers are European countries and the U.S., while the largest receivers are Kazakhstan, Russia, South Africa, and Southeast Asian countries.

To put our results in perspective, it is useful to compare them with real-world commitments of high-income countries for meaningful mitigation actions in low- and middle-income regions. For instance, at the 15th Conference of Parties (COP15) of the UNFCCC in Copenhagen in 2009, high-income countries committed to a collective goal of mobilizing $100 billion per year by 2020. The goal was formalized at the COP16 in Cancun, and, at the COP21 in Paris, it was reiterated and extended to 2025. According to a monitoring report of the OECD, a total of USD 83.3 billion in climate finance was provided and mobilized by high-income countries in 2020, falling short of the pledged amount (OECD, 2022).

In the comparison with the "USD 100 billion per year" pledge of the successive COPs, our model suggests that in the presence of a global carbon tax, the transfers needed to equalize the economic costs of climate action across countries amount to USD 272 billion. While this is substantially larger than the latest pledge achieved (by a factor 3), the impact this would have on the population of developed countries is in fact relatively modest. The highest transfers need to be paid by Ireland in the amount of $2,000 per person per year, and by Switzerland in the range of $1,400 per person per year. For the rest of the EU members and the U.S., the effective amount that should be paid by an individual in a year does not exceed $1,000. Note that because poor countries tend to have larger populations, the

[14] While being already quite rich, Bahrain and Saudi Arabia are heavily penalized by the carbon tax as their main economic activity is oil production (albeit with the greenest emission intensities in the data for the sectors of mining and energy). Since our scenario only cares about making the economic cost of the tax equal across countries and ignores entirely geopolitical considerations, they become large beneficiaries of such transfers.

Figure 16: Fair Tax: Changes in Real Income

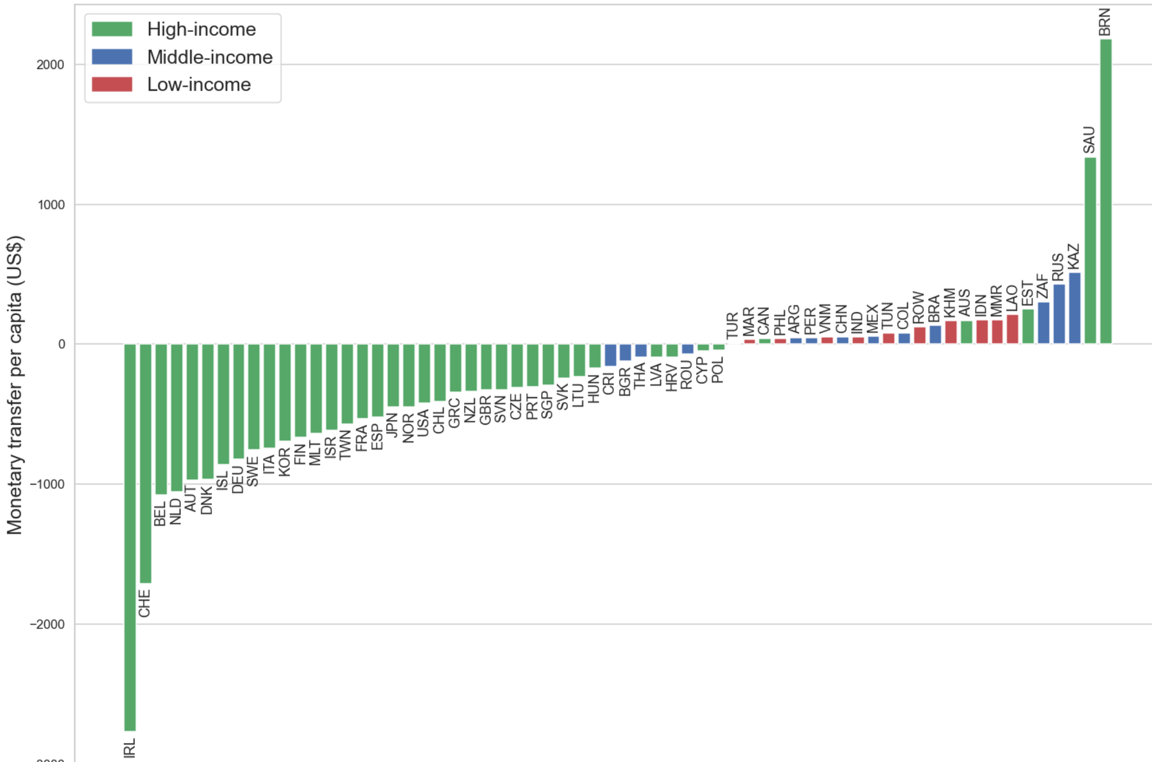


effective transfers received per capita are lower (e.g., \$600 per capita for Kazakhstan, less than \$200 for Laos and Indonesia). The equal-costs scenario therefore suggests that in absence of any geopolitical consideration, socio-economic equality in the face of optimal climate action can be achieved with modest transfers.

4.2.2 Polluter-pays transfers

We now turn to the international monetary transfers associated with a polluter-pay scheme. Recall that our polluter-pay scheme aims at quantitatively simulating the principle of Common but Differentiated Responsibilities, which seeks to address fairness in climate action by acknowledging that all states have a shared obligation to address environmental destruction but denies equal responsibility of all states with regard to environmental protection. While 30 years old, this principle has only recently been brought back as a leading principle supporting climate negotiations, in particular in the Paris Agreements. For

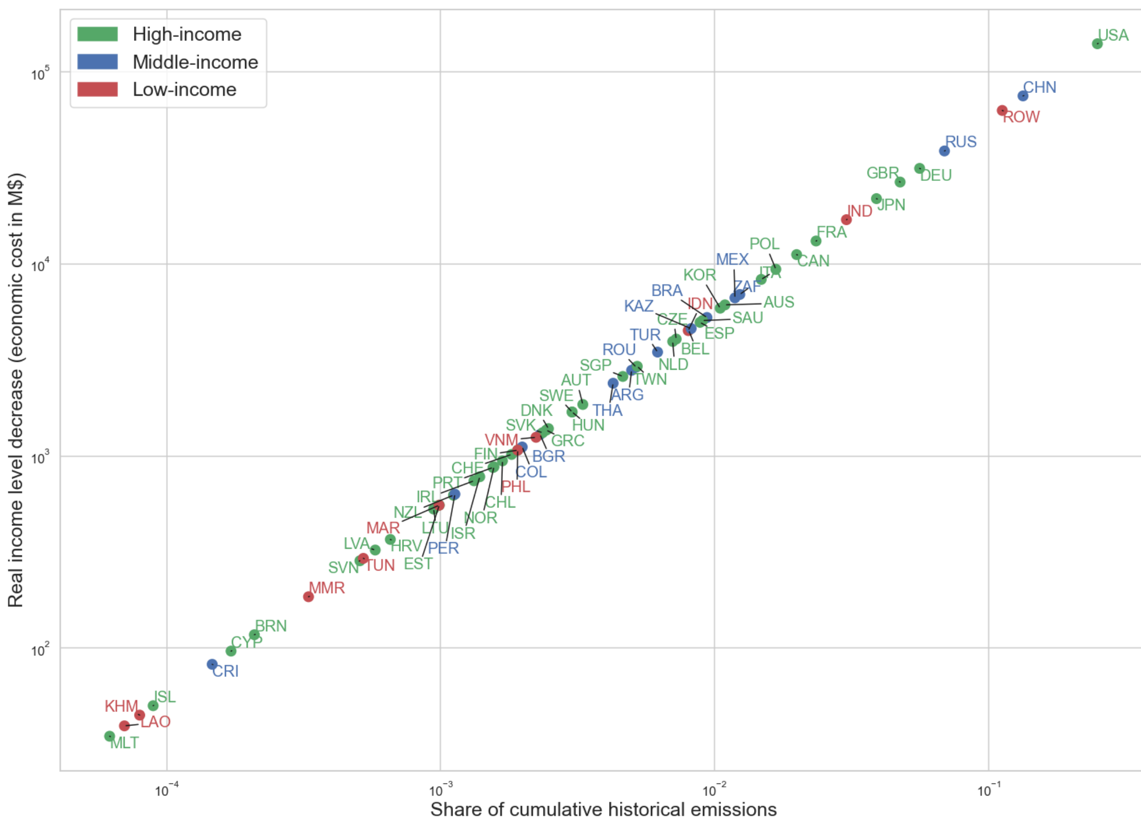
Figure 17: Fair Transfers



instance, the tone generally set in the 2022 Conference of Parties of the UNFCCC (COP27) suggests that simple fairness in the distribution of the economic costs of climate action - as in our "equal costs" transfers scheme - is politically not enough.

Our polluter-pays scheme incorporates this geopolitical perspective and is designed to comply with the CBDR by making sure that the realized real-income cost borne by a country is proportional to its historical contribution to global cumulative emissions. Figure 18 shows that the transfers successfully achieve that by ensuring an exact correlation between the real income costs that follow the adoption of the global carbon tax paired with polluter-pays transfers (in millions of US dollars) and the share of cumulative historical emissions. This means, for instance, that the economic cost of the global carbon tax for the U.S. needs to be 25% of the aggregate economic costs, the economic cost for China 13%, and the economic cost of Brazil 1%, as those are the relative contributions of each country to total emissions of greenhouse gases. Similar to the equal-costs case, the overall impact of the polluter-pays scenario is

Figure 18: Polluter Pays Transfers: Changes in Real Income

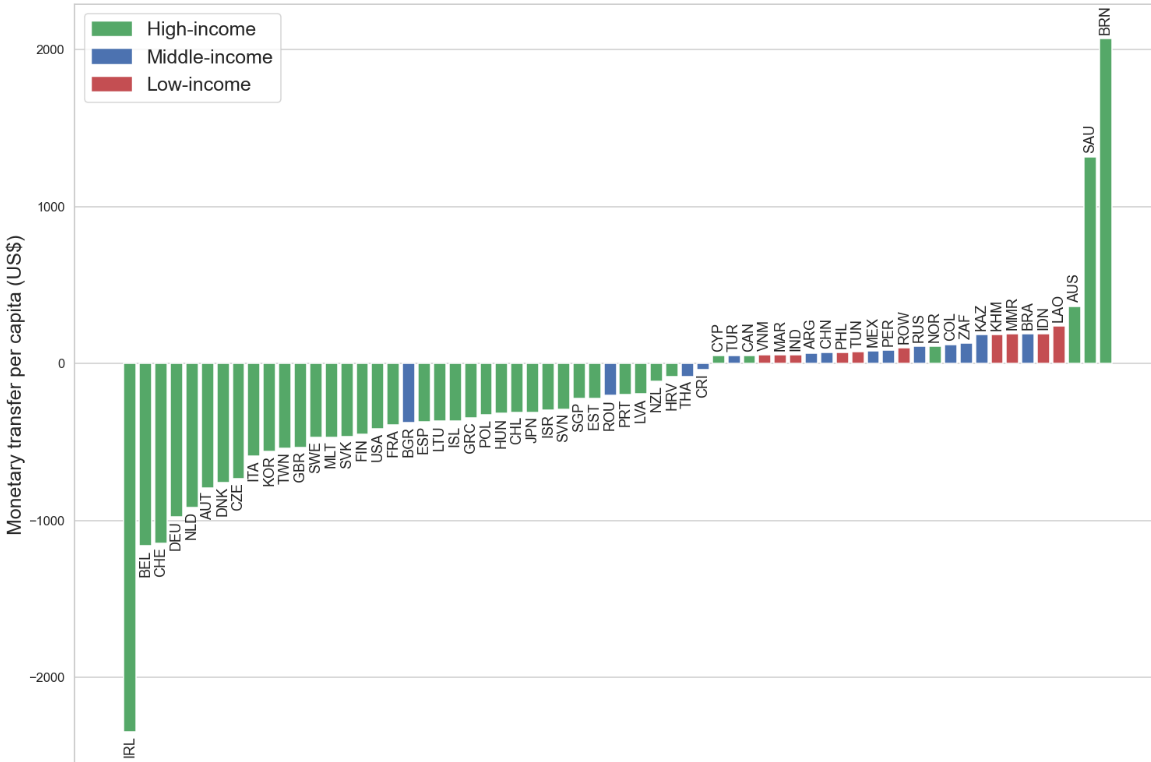


also smoother than climate action without redistribution: the global reduction of emissions remains at –28%, the global real income cost remains at –0.7%, and the decline in gross output remains lower at –2.1%.

In terms of transfers, three important facts can be emphasized. First, the total amount of transfers required is slightly lower than in the equal-cost scenario at USD 255.7 billion. This is because the equal-costs scenario is focused solely on redistributing economic costs equally, whereas the polluter-pays scenario allows for unequal economic costs based on historical responsibility. As a result, per-capita transfers will also be lower, the maximum amount required being now less than \$2,000 per person per year (still paid by Ireland)

Second, the distribution of transfers across countries still implies that high-income countries should pay and low- and middle-income countries should receive, as shown by Figure 19. There is a clear positive correlation between current per-capita GDP and historical contribution to global cumulative

Figure 19: Polluter Pays Transfers



emissions. This should not be particularly surprising as countries that benefited from the Industrial Revolution started to emit CO_2 during the 19th century and have now the highest levels of development.

Third, the differences in the distribution of transfers implied by the equal-costs and by the polluter-pays scenarios (comparing Figures 17 and 19) are revealing of countries' current and historical responsibilities in climate change. Countries that ought to pay a transfer in the equal costs world remain payers in the polluter-pays scenario, but their relative contributions change, to reflect individual countries' weight in historical emissions. For example, France's effective transfer per capita is now lower than that of Great Britain, because France's historical energy sector has focused on carbon-neutral nuclear power, while Great Britain's energy mix has been historically borne by coal and later oil and gas.

Similarly, receiving countries in the equal-costs scenario remain so in the polluter-pays scenario, albeit receiving different amounts. This is for example the case of Russia: because Russia is a large producer of natural gas (which belongs in our data to the energy sector, one of the sectors with the highest emission intensity), it is heavily penalized by the carbon tax (see Figure 8, Russia has an effective tax rate of 6% when the global carbon tax is set at \$100/tCO_2e). In the equal costs scenario, Russia received transfers of \$404 per capita, in order to bring its real-income cost to par with other countries. Russia is, however, also a historical polluter so that in the polluter-pays scenario, its effective per-capita transfers are decreased to less than \$80 per person per year. The opposite is true of Brazil: Currently, the third largest exporter of agricultural products globally, Brazil's real income loss in response to a \$100/tCO2 without redistribution is relatively high (–1.8%, to be compared to the global cost of –0.7%). In the equal-costs scenario, this implies that Brazil receives per capita transfers of \$115. However, Brazil only recently started to contribute to cumulative emissions (albeit at accelerating rate, with a current contribution of 1%). This is taken into account in the polluter-pays scenario so that Brazil receives per capita transfers of \$170 in this case.

One constant in the comparison between the two scenarios is that countries that were receivers in the equal-costs scenario remain receivers in the polluter pays scenario, and payers remain payers. suggests that a polluter-pays scheme could perhaps be a better redistribution mechanism: fairness is still somewhat achieved while respecting the politically desired principle of Common but Differentiated Responsibilities.

5 Heterogeneous Carbon Pricing

In this section, we ask what heterogeneous carbon pricing schemes - with countries adopting different levels of carbon taxation - would imply for fairness in climate action. Such schemes are often seen as more politically feasible, as they eliminate the need for coordination among all countries, as well as fairer, as they reduce the depth of carbon taxation in low and middle-income countries. We investigate the following two policy options, which feature prominently in the policy debate: (i) a unilateral carbon pricing scheme amongst a selected "club" of countries with Carbon Border Adjustment Mechanism (CBAM), as is currently being implemented in the European Union (EU), and (ii) heterogeneous carbon prices based on income levels following a recent proposal by the International Monetary Fund (IMF)(Parry et al., 2021).

When investigating each scenario, we focus on the following question: does the proposed scheme introduce more or less fairness between the economic North and the economic South? To answer this question we compare the proposed policy with a clear benchmark: a counterfactual world generating the same emissions reduction as in the scenario analyzed with a global and uniform carbon tax paired with "equal costs" transfers aimed at equalizing the real income cost across countries. By keeping the reduction in emissions fixed, we can isolate the effects of price heterogeneity in delivering fairness. The goal is to compare the amount of North-South transfers required to maintain an equal real-income cost for all countries.

5.1 Climate Club with a Carbon Border Adjustment Mechanism

To model the scenario of a climate club with a carbon border adjustment, we build on the design of the EU CBAM. The EU Carbon Border Adjustment Mechanism (CBAM) has been imagined in response to the EU Emissions Trading Scheme (ETS) to allow European companies to remain competitive in a world where the EU imposes a unilateral carbon price on its producers. In simple terms, one can consider the EU ETS as a carbon producer tax: any European producer must pay for a right to emit GHG emissions over the course of their production process. This makes the price of their output relatively more expensive, and therefore less attractive than foreign goods produced with no carbon tax. To restore the competitiveness of these producers within the EU, the CBAM imposes a similar carbon price on the consumption of foreign goods imported into the EU if no carbon tax has been applied on them prior to entry.

To understand what the creation of a CBAM would imply for fairness in climate action, we simulate the creation of a club with a critical mass of countries from the Global North and South: members of the EU, the U.S., China, India, Indonesia, Russia, Brazil and South Africa. Members of the club impose a carbon tax of $100/tCO2eq on their producers, while simultaneously imposing a consumption tax on all imports coming in. We selected this group of countries because they are the "key players" driving down emissions in the uniform carbon tax scenario. For instance, when they are the only ones adopting a USD 100/tCO2eq tax, an 18.5% reduction of global emissions is achieved, that is, already two thirds of the maximum achievable. Notice that a club with a CBAM formed by this group of countries implies that a carbon price is not adopted by the majority of low and middle-income countries that are outside of it.

Results show that a climate club with "key players" would imply a global welfare cost 10.6% larger than the scenario of a uniform global carbon tax, assuming that carbon is priced at a level such that the obtained global emissions reduction is identical (in this case, equivalent to -19%). This corresponds to a world with a carbon price of USD 60/tCO2eq. In other words, such a climate club is relatively less efficient than a uniform global carbon tax.

But what would our definition of the climate club imply in terms of fairness? Comparing North-South transfers needed to equalize the real-income cost of carbon pricing for all countries with our climate club to our uniform global carbon tax with "fair" transfers benchmark, we find that our climate club is in fact less fair, to the extent that it requires transfers of the order of USD 201 billions, that is 36% more than in our benchmark scenario. Hence, the argument according to which heterogeneous carbon pricing would be fairer does not hold here. The concept of a climate club may be politically attractive to the extent that it only requires the coordination of a few key players. But the ideal group of key players that we have identified (E.U., U.S., China, India, Indonesia, Russia, Brazil, and South) is not homogeneous, both in terms of economic performance and in terms of historical responsibility towards climate change. This may partially explain why our climate club scenario is in fact less fair than a uniform carbon tax.

5.2 IMF International Carbon Floor Pricing

International Carbon Floor Pricing (ICPF) is a proposal made by the IMF in June 2021 with the key ambition to match near-term climate goals with credible policy actions (Parry et al., 2021). To paraphrase the proposal, the scheme would rely on two key ingredients: (i) a small number of key large emitting countries would be the core "club" negotiating it, and (ii) the negotiation would focus on the minimum carbon price that each country must put on their CO2 emissions. The argument in favor of a core "club" of members is to simplify negotiations by limiting the size of the initial set-up. Candidates retained in the proposal are either a group composed of Canada, China, the European Union, Great Britain, India, and the United States, or the whole of the G20. Focusing the negotiations on the floor prices is in essence proposing a compromise between a global uniform carbon tax as advertised by the economists, and a climate club scenario similar to what we studied above. In their calibration, the IMF proposes three floor prices: $75/tCO2eq for advanced countries, $50/tCO2eq for high-income emerging economies (EME), and $25/tCO2eq for low-income EMEs.

In our simulations, we analyze the two scenarios proposed by the IMF - a club composed of Canada, China, the European Union, Great Britain, India, and the United States, as well as all G20 economies - plus a scenario in which all countries are participating of the ICPF, according to their level of economic development.[15] Again, we compare the welfare cost and the monetary transfers required between the economic North and the economic South in order to equalize per-capita real-income changes across countries in the ICPF scenarios with the same metrics of a uniform carbon tax scenario achieving the same emissions reduction.

We find that the ICPF scenario of the IMF including only Canada, China, the European Union, Great Britain, India, and the United States is in fact the least fair of all, to the extent that the amount of North-South transfers needed would be 4.6% higher than with a global uniform carbon tax. In comparison transfers needed with a IPCF including G20 countries would require transfers 1.2% higher than in its uniform tax benchmark, and thus remain less fair. The IPCF applied to all countries would be the fairest to the extent that it would require 5.5% less transfers than a uniform carbon tax with fair transfers.

What about efficiency? The IPCF scheme on the restricted group of countries proposed by the IMF (Canada, China, the European Union, Great Britain, India, and the United States) is not only the least fair but also the least efficient of these schemes, with a measured welfare cost 1.3 times larger than for a uniform carbon tax (132%). None of the studied scenarios appear more efficient than their uniform "fair" tax benchmark. However, it is clear that the more countries included in the scheme, the lower the inefficiency. The "most efficient" is thus the IPCF applied to all countries, with additional welfare costs restricted to a 12% increase.

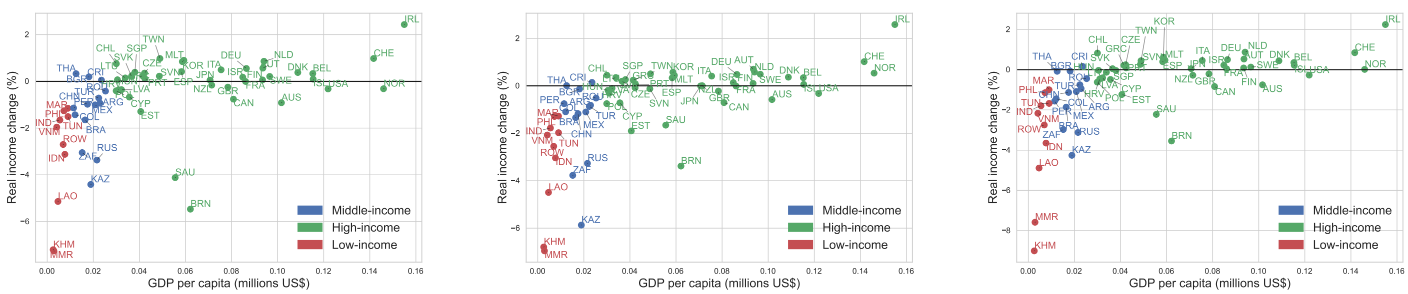
To sum it up, it is unclear whether the IMF proposal would be so much fairer than a simple global uniform carbon tax paired with North-South transfers (as already committed by a certain amount of countries). Indeed, the IMF ICPF scheme applied to all countries of the world would be 12% more costly in terms of real income change, while reducing the required transfers by a mere 6%.

[15] We follow the World Bank allocation of countries to different levels of economic development in our simulations: https://datatopics.worldbank.org/world-development-indicators/the-world-by-income-and-region.html.

6 Robustness

In this section, we test the robustness of our results for different values of the trade elasticity. The main part of the paper estimates the elasticities using the method in Caliendo and Parro (2015). Additionally, we examine the result for two other sets of elasticities: First, we take the elasticities in Fontagné et al. (2022) and aggregate them to our sectoral definition. Second, we use the method in Fontagné et al. (2022) and estimate the elasticities with our data, combining it with tariff data from Fontagné et al. (2022). More details on how the elasticites are estimated can be found in Appendix C.

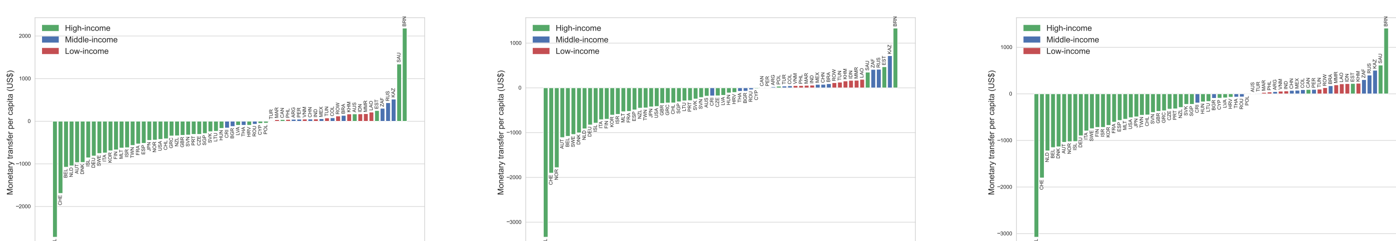
Figure 20 shows the changes in real income for each country for all three sets of elasticities. The overall picture is very similar: high-income countries gain, while low- and middle-income countries lose. The actual percentage change for the real income change is slightly different for each elasticity and depends on which sectors the countries specialize in. Saudi-Arabia for example will have a lower real income decrease with the aggregated and the Fontagne elasticities. The reason is that the elasticities for mining are much higher for those two methods, so that a carbon tax induces a larger reallocation from that sector since they are more substitutable.



(a) Caliendo-Parro estimation (b) Aggregated elasticities (c) Fontagne elasticites

Figure 20: Real income and GPD

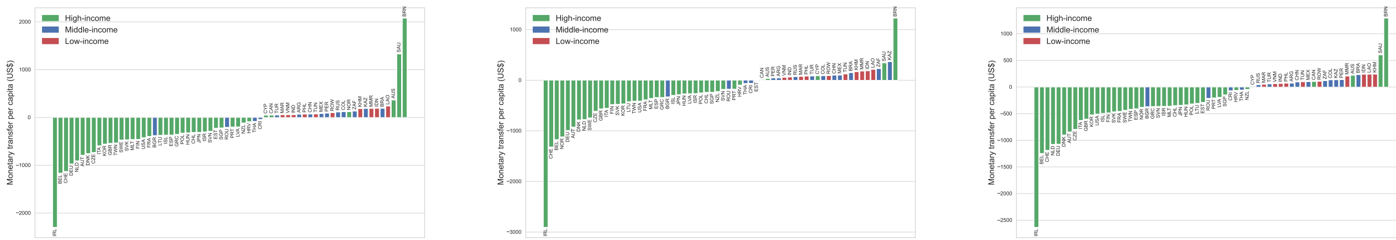
Figure 21 shows the results for the equal cost transfers for each elasticity.



(a) Caliendo-Parro estimation (b) Aggregated elasticities (c) Fontagne estimation

Figure 21: Equal cost transfers

Figure 22 shows the results for the polluter pays transfers for each elasticity.



(a) Caliendo-Parro estimation (b) Aggregated elasticities (c) Fontagne estimation

Figure 22: Polluter pays transfers

Observe that the magnitude of the transfers may vary with the different estimation methods. For instance, transfers received by Bahrain and Saudi Arabia are lower when they are backed out with the elasticities from Fontagné et al. (2022) or the ones estimated using their method. In this case, this happens because the Caliendo and Parro elasticity in the Mining and Energy sector, which is disproportionally important for these two countires, is relatively lower, as described in Table 1. This difference magnifies the negative impact of the carbon tax through a more severe terms-of-trade loss, thus requiring higher transfers to equalize the welfare costs of climate action. Still, notice that the main conclusions of the paper are robust to the different elasticities: irrespective of the type of transfer, the cross-country distribution implies that high-income countries should pay and low- and middle-income countries should receive them.

7 Conclusion

In this paper, we conduct a quantitative analysis of the principle of Common but Differentiated Responsibilities (CBDR), recognizing that low- and middle-income countries are most vulnerable to climate hazards despite their minimal contributions to climate change. We utilize a modern, multi-country, multi-sector quantitative trade model to assess how policies non-compliant with CBDR affect the Global South and explore alternative transfer schemes that could render optimal climate policy politically feasible. Furthermore, we examine the fairness of policy proposals relying on heterogeneous pricing, which are prominently debated in policy circles.

Our findings indicate that while a uniform carbon tax effectively reduces global emissions, it disproportionately impacts low- and middle-income countries, exacerbating economic inequalities between nations. These countries bear less historical responsibility for emissions and are more susceptible to climate impacts, yet they face real income losses up to 7%, in stark contrast to the potential income gains observed in high-income countries. Our analysis suggests that redistribution mechanisms designed to socialize the costs of climate action or to account for historical GHG emission patterns could mitigate this disparity. Implementing such mechanisms would require tripling current climate finance levels, representing a relatively modest per capita cost for high-income countries. Additionally, we find that heterogeneous pricing schemes, such as a climate club with a Carbon Border Adjustment Mechanism (CBAM) or the recent IMF carbon taxation proposal, while politically feasible, do not necessarily lead to fairer outcomes compared to global policies.

This study opens several avenues for future research. An exploration of how technological innovation or diffusion, particularly in clean energy driven by carbon taxation, could alter the impact of climate action on inequality would be valuable. Further research could also investigate the heterogeneity in climate damages in light of CBDR by relating our findings to estimations of the social costs of carbon by individual countries.

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A Data treatment

Aggregations

To avoid sparseness of the input output table and zero gross outputs, we aggregate the following countries:

- Luxembourg and Belgium: subsequently labeled `BEL` in all data
- Hong-Kong and China: subsequently labeled `CHN`
- Malaysia and Singapore: subsequently labeled `SGP`

as well as the following sectors:

- 'Mining and quarrying, energy producing products' [D05T06] with 'Mining support service activities' [D09]: subsequently labeled as [D05T06] (Mining, energy)
- 'Motor vehicles, trailers and semi-trailers' [D29] with 'Other transport equipment' [D30]: subsequently labeled [D29T30] (Transport equipments)

These aggregations leave us with a sample of 64 countries (incl. ROW aggregate) and 42 sectors from 1995 to 2018.

ICIO

The raw ICIO tables records negative values for some accounts of final consumption or value added. As the model cannot accommodate these negative values, we redistribute the negative parts in the table while respecting the following constraints:

- the sum of the columns and the sum of the rows must remain equal,
- the technical coefficients within the IO table (intermediate input spending over gross output ratio, corresponding to the parameters γ in the model) must remain constant equal to the raw ratios.

FAO

We keep only FAO Tier 1 emissions by subcategories belonging to the category 'Agricultural Land' with the exception of 'On-farm Energy Use', since these emissions are already contained in the TECO2 emission data.[16] The remaining observations are then aggregated into the 64 countries with the ROW aggregate and are assigned to the 'Agriculture' sector.

EDGAR

We first combine different time series extracts of the EDGAR database, namely the 'CH4', 'CO2_excl_short-cycle_org_C' and 'N2O' data sheet by converting the emissions into CO_2 equivalents according to the respective AR4 100-year GWP value.[17] We then aggregate the data into our 63 sample countries and create the ROW aggregate with the remaining countries. To assign the IPCC emission categories to our various sample sectors, we rely on the exact definition of the IPCC emission category compared to the ISIC rev.4 codes comprised in our sample sector definition.

For IPPC category 'industrial process and product use emissions' (chapter 2), we apply the following conversion:

IPCC category	Name	Sample sector
2.A	Mineral Industry	Non-metallic minerals
2.B	Chemical Industry	Chemicals
2.C	Metal Industry	Basic metals
2.E	Electronics Industry	Electronic
2.F	Product Uses As Substitutes For Ozone Depleting Substances	Energy

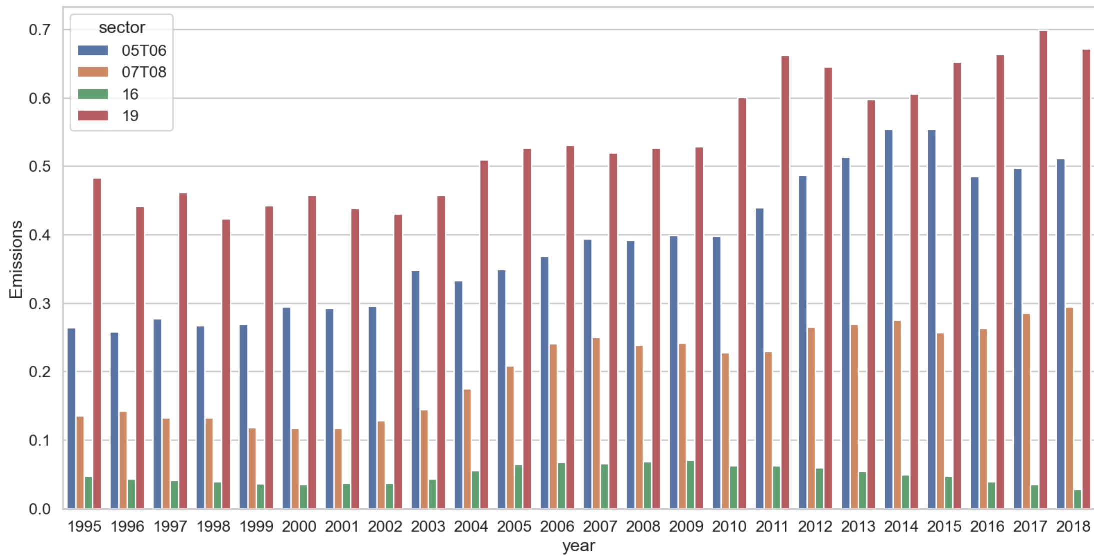
For the IPCC categories "fugitive emissions" (chapter 1.B) we proceed in two steps. Based on the categories definitions we have a direct mapping for the subcategory 'Oil and Natural Gas' (1.B.2) assigned to the sample sector 'Mining, energy'. The subcategory 'Solid Fuels' (1.B.1) however matches with different sample sectors: 'Mining, energy', 'Mining, non-energy', 'Wood', and 'Coke, petroleum'. We therefore disaggregate the IPCC aggregate "Solid fuelds" into the respective sample sectors by using

[16] The category 'Agricultural Land' includes the following subcategories: 'Fires in humid tropical forests', 'Fires in organic soils', 'Net Forest conversion', 'Drained organic soils', 'Synthetic Fertilizers', 'Crop Residues', 'Manure left on Pasture', 'Manure applied to Soils', 'Manure Management', 'Enteric Fermentation', 'Savanna fires', 'Burning - Crop residues', 'Rice Cultivation', 'On-farm Energy Use'

[17] The AR4 100-year GWP values are 25 for CH_4 and 298 for N_2O.

as a disaggregation weights the share of emissions from fuel burning of each sample sector in the total.[18] This procedure results in disaggregated emissions as presented in Figure 1.

Figure 23: Sectoral emission disaggregation



Notes on data uncertainty

Direct emissions from land use, chemical processes or fugitive emissions are difficult to measure or estimate. As a result, the data we use to complement emissions from fuel consumption is subject to large uncertainty ranges. These ranges are reported for the EDGAR database (and covers the agricultural emissions obtained in the FAO as well).

B Solving algorithm

In this section, we detail how we reduce the model to a $N \times S$ system that we use to back out counterfactual results. The aim is to reduce the number of variables, while keeping the system as linear as possible.

Equations (8) and (9) imply that :

$$\widetilde{q}_{is'j} = \widetilde{I}_j \widetilde{q}_{is'j}{}^{\circ} \tag{20}$$

[18]Note that we did not include the IPCC categories 2.D 'Non-Energy Products From Fuels and Solvent Use' and 2.G 'Other Product Manufacture and Use' since a clean mapping from the IPCC categories to the corresponding sample sectors is not as easily separable.

where $\widetilde{q}_{is'j}^{\circ} = [\widetilde{p}_{is'}(1+t^e_{is'j})]^{-\sigma_{s'}} \widetilde{P}^{c}_{s'j}{}^{(\sigma_{s'}-1)}$ only depends on the change of prices and the baseline. Useful to note that his inverse is linear in any change of set of prices : $\widetilde{q}_{is'j}^{\circ}(\alpha\widetilde{p}) = \widetilde{q}_{is'j}^{\circ}(\widetilde{p})/\alpha$. This is the most general expression of the change of quantities traded so that the condition of consumer spending is respected by construction because : $\sum_{i,s'} \widetilde{p}_{is'}(1+t^e_{is'j})\widetilde{q}_{is'j}^{\circ}(p^B_{is'j}q^B_{is'j}) = I^B_j$. The form of this expression represents that if the income of the consumer increases (or decreases), he will proportionally increase his consumption from every country/sector. $\widetilde{q}_{is'j}^{\circ}$ contains all the information of the reorganisation of his consumption if his income didn't change in the counterfactual world.

Similarly, for intermediates, equation (10) together with $\widetilde{E}_{s'js} = \widetilde{E}_{js}$ imply that :

$$\widetilde{m}_{is'js} = \widetilde{E}_{js}\widetilde{m}_{is'js}^{\circ} \tag{21}$$

where $\widetilde{m}_{is'js}^{\circ} = [\widetilde{p}_{is'}(1+t^e_{is'j})]^{-\eta_{s's}} \widetilde{P}^{\pi}_{s'js}{}^{(\eta_{s's}-1)}$ has the same properties as $\widetilde{q}_{is'j}^{\circ}$. The construction makes sure that the producer spending is respected.

Having the consumer and producer spending respected by construction, we need to compute the consumer and producer revenue. We use equations (15) with $\widetilde{E}_{js} = \widetilde{Y}_{js}$ to compute the wages change under a change of spending of the producer:

$$\widetilde{w}_j = \frac{\sum_s \widetilde{E}_{js} L^B_{js}}{L_j} \tag{22}$$

We have then made sure that the solution respects the labor market clearing condition and the constitutive equation of production $L_{js} = \gamma_{j,Ls}\frac{Y_{js}}{w_j}$, and we can write the consumer revenue and producer spending from the consumer and producer clearing equations :

$$\widetilde{I}_j I^B_j = \sum_s \widetilde{E}_{js} L^B_{js} w^B_j + \sum_{i,s'} \widetilde{I}_j \widetilde{p}_{is'} t^e_{is'j} \widetilde{q}_{is'j}^{\circ}(p^B_{is'j}q^B_{is'j}) + \sum_{i,s',s} \widetilde{E}_{js}\widetilde{p}_{is'} t^e_{is'j}\widetilde{m}_{is'js}^{\circ}(p^B_{is'j}m^B_{is'js}) + D^B_j \tag{23}$$

$$\widetilde{E}_{is'} E^B_{is'} = \sum_j \widetilde{I}_j \widetilde{p}_{is'}\widetilde{q}_{is'j}^{\circ}(p^B_{is'j}q^B_{is'j}) + \sum_{j,s} \widetilde{E}_{js}\widetilde{p}_{is'}\widetilde{m}_{is'js}^{\circ}(p^B_{is'j}m^B_{is'js}) \tag{24}$$

We then use (23) in (24):

$$\widetilde{E}_{is'}E^B_{is'} = \widetilde{p}_{is'}\left(\sum_{j,s}\widetilde{E}_{js}\left[\widetilde{q}_{is'j}{}^{\circ}(p^B_{is'j}q^B_{is'j})\frac{L^B_{js}w^B_j + \sum_{i,s'}\widetilde{m}_{is'js}{}^{\circ}\widetilde{p}_{is'}t^e_{is'j}(p^B_{is'j}q^B_{is'j})}{I^B_j - \sum_{i,s'}\widetilde{q}_{is'j}{}^{\circ}\widetilde{p}_{is'}t^e_{is'j}(p^B_{is'j}q^B_{is'j})} + \widetilde{m}_{is'js}{}^{\circ}(p^B_{is'j}m^B_{is'js})\right]\right.$$
$$\left. + \sum_j \frac{D_j\widetilde{q}_{is'j}{}^{\circ}(p^B_{is'j}q^B_{is'j})}{I^B_j - \sum_{i,s'}\widetilde{p}_{is'}t^e_{is'j}\widetilde{q}_{is'j}{}^{\circ}(p^B_{is'j}q^B_{is'j})}\right) \tag{25}$$

$$\widetilde{p}_{js} = \left(\sum_{s'}\widetilde{E}_{js'}\frac{L^B_{js'}}{L_j}\right)^{\gamma_{j,Ls}} \prod_{s'} \widetilde{P}^{\pi}_{s'js}{}^{\gamma_{s'js}} \tag{26}$$

with the last equation expressing the cost of production from the solution of the cost minimization of the production costs of the producer (12). We have thus reduced the equations to a system of two non-linear equations (25) and (26) of the two fundamental hat quantities $(\widetilde{E}, \widetilde{p})$. Since we have explicit expressions of the variables on the right hand side, we can solve numerically this system with a nested fixed point routine.

The solution space of this system of equations is of dimension 1, any linear transformation $\alpha(\widetilde{E}_{\text{sol}}, \widetilde{p}_{\text{sol}})$ of a solution of the system is also solution. We need to add one numeraire constraint to make the solution unique.

$$\widetilde{X}_{\text{numeraire}} = 1 \tag{27}$$

The numeraire can be any quantity constructed with a linear combination of $(\widetilde{E}_{\text{sol}}, \widetilde{p}_{\text{sol}})$. We use the wage in the USA as a numeraire, so we need to enforce that $\widetilde{E}_{\text{sol}}$ respects :

$$\sum_{s'}\widetilde{E}_{USA,s'}\frac{L^B_{USA,s'}}{L_{USA}} = 1 \tag{28}$$

So we can solve for any solution $(\widetilde{E}_{\text{sol}}, \widetilde{p}_{\text{sol}})$ of (25) and (26) and construct :

$$\left(\frac{\widetilde{E}_{\text{sol}}}{\sum_{s'}\left(\widetilde{E_{\text{sol}}}_{USA,s'}\frac{L^B_{USA,s'}}{L_{USA}}\right)}, \frac{\widetilde{p}_{\text{sol}}}{\sum_{s'}\left(\widetilde{E_{\text{sol}}}_{USA,s'}\frac{L^B_{USA,s'}}{L_{USA}}\right)}\right) \tag{29}$$

that is the unique solution that respects (25), (26) and (28). Our results are robust to other choices of numéraire, such as global GDP or total global output.

C Elasticity estimation

Table 1 shows the elasticities for the different estimation methods. Most methods to estimate elasticities rely on the gravity equation, which maps trade flows to trade costs like distance and tariffs. Column 3 shows the simplest method we use: We take existing elasticities and map them to our sector categorization. For that, we use the elasticities in Fontagné et al. (2022) and aggregate them so that on average, they yield the number 4 which is in line with the preferred elasticity in Head and Mayer (2014). The aggregation is necessary because we have a much less granular sectoral composition than Fontagné et al. (2022). The fourth column relies on the estimation method in Fontagné et al. (2022), where we use lagged tariffs as instruments for the tariffs in a regression of the gravity equation. For that, we use the tariff data in Fontagné et al. (2022), aggregate it to our level of sectoral aggregation, and combine it with our trade flow data. To estimate the elasticities, we regress log tariffs on log trade flows, together with multilateral resistance terms, importer-year, and exporter-year fixed effects. Three-year lags of tariffs serve as instruments for the tariffs. All results in the main part of the paper are based on the elasticities in the last column which we estimate along the lines of Caliendo and Parro (2015). This method uses a fixed-effects strategy to isolate the effect of trade costs on trade flows. We use all years of the data to create the fixed-effects following Caliendo and Parro (2015). We replace elasticities that have the wrong sign, are insignificant, or cannot be estimated due to a lack of tariff data by the mean.

Table 1: Elasticities

Sector	Sector Names	Agg Elasticity	FG Elasticity	FG SE	CP Elasticity	CP SE
01T02	Agriculture	3.48	8.27	0.69	4.95	0.14
03	Fishing	3.45	2.47	0.46	2.58	0.10
05T06	Mining, energy	10.38	5.08	1.14	1.78	0.26
07T08	Mining, non-energy	9.14	4.58	1.04	3.29	0.23
10T12	Food products	3.15	6.31	0.44	4.05	0.14
13T15	Textiles	3.44	5.75	0.56	5.17	0.14
16	Wood	2.97	5.69	0.58	5.02	0.13
17T18	Paper	3.81	6.86	0.62	4.54	0.14
19	Coke, petroleum	5.96	0.00	1.41	-1.27	0.29
20	Chemicals	4.49	6.72	0.85	3.77	0.19
21	Pharmaceuticals	4.97	5.33	1.08	4.10	0.23
22	Plastics	3.00	6.19	0.55	4.17	0.13
23	Non-metallic minerals	3.41	5.36	0.73	3.68	0.16
24	Basic metals	6.25	7.19	1.14	5.86	0.24
25	Fabricated metals	2.65	5.89	0.66	4.87	0.14
26	Electronic	2.84	5.63	0.72	2.19	0.16
27	Electrical equipment	2.59	6.00	0.58	3.24	0.13
28	Machinery	2.93	6.02	0.63	2.91	0.14
29T30	Transport equipments	3.93	NA	NA	NA	NA
31T33	Manufacturing nec	3.13	6.56	0.61	4.90	0.14
35	Energy	3.76	1.71	0.47	3.78	0.13
36T39	Water supply	6.55	5.05	1.12	1.91	0.21
41T43	Construction	3.05	NA	NA	NA	NA
45T47	Wholesale, retail	3.05	NA	NA	NA	NA
49	Land transport	3.05	NA	NA	NA	NA
50	Water transport	3.05	NA	NA	NA	NA
51	Air transport	3.05	NA	NA	NA	NA
52	Warehousing	3.05	NA	NA	NA	NA
53	Post	3.05	NA	NA	NA	NA
55T56	Tourism	3.05	NA	NA	NA	NA
58T60	Media	5.36	5.15	0.81	4.03	0.17
61	Telecom	3.05	NA	NA	NA	NA
62T63	IT	3.05	NA	NA	NA	NA
64T66	Finance, insurance	3.05	NA	NA	NA	NA
68	Real estate	3.05	NA	NA	NA	NA
69T75	R&D	5.57	2.38	0.71	3.76	0.15
77T82	Administration	4.71	2.62	0.55	2.46	0.10
84	Public sector	3.05	NA	NA	NA	NA
85	Education	5.66	2.78	0.52	2.80	0.11
86T88	Health	3.05	NA	NA	NA	NA
90T93	Entertainment	4.71	3.22	0.56	2.29	0.11
94T98	Other service	3.05	NA	NA	NA	NA

D Optimal Carbon Tax in Multi-Sector Armington (1969)

This characterizes the optimal carbon tax in a multi-sector Armington model with environmental externalities. The solution follows the primal approach. First, I solve the hypothetical problem of a government that can freely choose output and consumption to maximize domestic utility. Second, I show that this optimal allocation can be implemented via a carbon tax in the decentralized equilibrium.

The implementation of the primal approach with many sectors follows the discussion by Caliendo and Parro (2022). The solution for the optimal carbon taxation scheme is similar to Hoel (1996).

D.1 Setup

There are two countries denoted by i and j. ij represents a flow from i to j. There are $S+1$ sectors, indexed by s. Sector $s=0$ is a dirty sector, whose production activity generates emissions, a pure global externality.

Preferences are given by:

$$U_i = \sum_s \alpha_j \ln\left[\left(c_{ii}^s\right)^{\frac{\sigma^s-1}{\sigma^s}} + \left(c_{ji}^s\right)^{\frac{\sigma^s-1}{\sigma^s}}\right]^{\frac{\sigma^s}{\sigma^s-1}} - \phi Z,$$

where $Z = \sum_i \sum_j c_{ij}^0$ are total carbon emissions, α_j is an expenditure share and ϕ is a climate damage parameter.

Technology is given by the following inverse production function:

$$l_i^s = \sum_j a_i^s c_{ij}^s,$$

where a_i^s are unit labor requirements and $\sum_s l_i^s = L_i$. The model abstracts from trade costs.

D.2 Planning problem

Consider the problem of a planner that chooses intra-national trade, imports and exports taking as given foreign wages w_j:

$$V_i(w_n) \equiv \max_{c_{ii}^s, c_{ij}^s, c_{ji}^s} \sum_s \alpha_j \ln\left[\left(c_{ii}^s\right)^{\frac{\sigma^s-1}{\sigma^s}} + \left(c_{ji}^s\right)^{\frac{\sigma^s-1}{\sigma^s}}\right]^{\frac{\sigma^s}{\sigma^s-1}} - \phi Z.$$

Home government solves this problem subject to resource constraints at home and abroad together with the trade balance condition.

D.2.1 Resource constraint at Home

$$\sum_s a_i^s[c_{ii}^s + c_{ij}^s] \leq L_i.$$

D.2.2 Trade balance condition

$$\sum_s \left[a_j^s w_j c_{ji}^s - p_{ij}^s(c_{ij}^s, w_j) c_{ij}^s \right] \leq 0.$$

where $a_j^s w_j$ is the price of foreign goods and $p_{ij}^s(c_{ij}^s, w_j)$ is the world price of domestic goods.

Notice that this price function $p_{ij}(c_{ij}^s, w_j)$ is implicitly defined using the optimal consumption of domestic goods from foreign:

$$c_{ij} = \frac{p_{ij}(c_{ij}^s, w_j)^{-\sigma^s}}{[a_j^s w_j]^{1-\sigma_s} + [p_{ij}(c_{ij}^s, w_j)]^{1-\sigma_s}} \alpha_s w_j L_j.$$

D.2.3 Resource Constraint of Foreign

$$\sum_s a_j^s \left[c_{ji} + \frac{[a_j^s w_j]^{-\sigma^s}}{[a_j^s w_j]^{1-\sigma^s} + [p_{ij}(c_{ij}^s, w_j)]^{1-\sigma^s}} \alpha_s w_j L_j \right] \leq L_j.$$

D.2.4 Lagrangian

$$\begin{aligned}
\mathcal{L}(c_{ii}^s, c_{ji}^s, c_{ij}^s, \lambda, \lambda^*, \mu, w_j) \equiv & \sum_s \alpha^s \ln \left[\left(c_{ii}^s\right)^{\frac{\sigma^s - 1}{\sigma^s}} + \left(c_{ji}^s\right)^{\frac{\sigma^s - 1}{\sigma^s}} \right]^{\frac{\sigma^s}{\sigma^s - 1}} - \phi Z \\
& - \lambda \left[\sum_s a_i^s [c_{ii}^s + c_{ij}^s] - L_i \right] \\
& - \lambda^* \left[\sum_s a_j^s \left[c_{ji}^s + \frac{\left(a_j^s w_j\right)^{-\sigma^s}}{\left(a_j^s w_j\right)^{1-\sigma^s} + \left[p_{ij}(c_{ij}^s, w_j)\right]^{1-\sigma^s}} \alpha_s w_j L_j \right] - L_j \right] \\
& - \mu \sum_s \left[a_j^s w_j c_{ji}^s - p_{ij}^s(c_{ij}^s, w_j) c_{ij}^s \right].
\end{aligned}$$

Notice that the Lagrangian is separable across sectors:

$$\mathcal{L}(c^s_{ii}, c^s_{ji}, c^s_{ij}, \lambda, \lambda^*, \mu, w_j) = \sum_s [F^s(c^s_{ii} c^s_{ji}, \lambda, \lambda^*, \mu, w_j) - \phi Z + g^s(c^s_{ij} \lambda, \lambda^*, \mu, w_j)],$$

where

$$\begin{aligned} F^s(c^s_{ii} c^s_{ji}, \lambda, \lambda^*, \mu, w_j) \equiv \alpha^s \ln \left[(c^s_{ii})^{\frac{\sigma^s - 1}{\sigma^s}} + \left(c^s_{ji}\right)^{\frac{\sigma^s - 1}{\sigma^s}} \right]^{\frac{\sigma^s}{\sigma^s - 1}} \\ - \lambda a^s_i c^s_{ii} \\ - \lambda^* a^s_j c^s_{ji} \\ - \mu a^s_j w_j c^s_{ji}. \end{aligned}$$

$$g^s(c^s_{ij} \lambda, \lambda^*, \mu, w_j) \equiv \mu p^s_{ij}(c^s_{ij}, w_j) c^s_{ij} - \lambda a^s_i c^s_{ij} - \lambda^* \frac{a^s_j [a^s_j w_j]^{-\sigma^s}}{[a^s_j w_j]^{1-\sigma^s} + [p_{ij}(c^s_{ij}, w_j)]^{1-\sigma^s}} \alpha_s w_j L_j.$$

Therefore, one can maximize the Lagrangian sector by sector and determine the optimal allocation sector by sector.

D.2.5 First Order Conditions

Next, I use the following notation: $U'^k_{nm} \equiv \frac{\partial U_m}{\partial c^k_{nm}}$.

$$\frac{\partial \mathcal{L}}{\partial c^0_{ii}} = 0 \rightarrow U'^0_{ii} - \phi - \lambda a^0_i = 0$$

$$\frac{\partial \mathcal{L}}{\partial c^s_{ii}} = 0 \rightarrow U'^s_{ii} - \lambda a^s_i = 0, \;\; s = 1, ..., S$$

$$\frac{\partial \mathcal{L}}{\partial c^0_{ji}} = 0 \rightarrow U'^0_{ji} - \phi - \lambda^* a^0_j - \mu a^0_j w_j = 0$$

$$\frac{\partial \mathcal{L}}{\partial c^s_{ji}} = 0 \rightarrow U'^s_{ji} - \lambda^* a^s_j - \mu a^s_j w_j = 0, \;\; s = 1, ..., S$$

$$\frac{\partial \mathcal{L}}{\partial c^0_{ij}} = 0 \rightarrow -\phi + \mu p^0_{ij}(c^0_{ij}, w_j) - \lambda a^0_i = 0$$

$$\frac{\partial \mathcal{L}}{\partial c_{ij}^s} = 0 \to \mu p_{ij}^s(c_{ij}^s, w_j) - \lambda a_i^s = 0,\ \ s = 1, ..., S$$

The FOCs for intra-national trade flows imply the following condition for the social optimum:

$$\frac{U_{ii}^{\prime 0} - \phi}{U_{ii}^{\prime k}} = \frac{a_i^0}{a_i^k}, \quad k = 1, ..., S \tag{30}$$

D.2.6 Decentralization

Let τ_i^C be a wedge between the ex-factory price and the consumer price of the dirty good. We have that the consumers' optimal consumption vector satisfies:

$$\frac{U_{ii}^0}{U_{ii}^k} = \frac{p_{ii}^0 + \tau_i^C}{p_{ii}^k}, \quad k = 1, ..., S$$

Consider the following carbon taxation scheme:

$$\tau_i^C = \frac{p_{ii}^k}{U_{ii}^k}\phi, \quad k \neq 0 \tag{31}$$

Notice that $\frac{p_{ii}^k}{U_{ii}^k}$ is independent of k for $k \neq 0$, so that the choice of k is arbitrary.

The adoption of carbon tax (31) implies:

$$\frac{U_{ii}^0 - \phi}{U_{ii}^k} = \frac{p_{ii}^0}{p_{ii}^k} = \frac{a_i^0}{a_i^k},$$

which is equivalent to the optimality condition (30). This shows that the competitive equilibrium with a carbon tax defined by (31) is equivalent to the social optimum derived from the planning problem.

An important point about τ_i^C is that it is not driven by any sector-specific parameters. As noted by Hoel (1996), the optimal carbon tax τ_i^C is equivalent to a monetary measure of the marginal cost of carbon emissions. To see this, notice that ϕ is the marginal environmental cost of carbon and $\frac{p_{ii}^k}{U_{ii}^k}$ are dollars per unit of utility for good k.