The Global Consumer Incidence of Carbon Pricing: Evidence from Trade

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Carbon pricing is often seen as regressive, disproportionately burdening low-income consumers. I show that higher prices following a carbon tax would be mildly regressive in industrialized countries, mildly progressive in developing countries, and steeply regressive across countries. Refunding revenues with national carbon dividends would reverse all three findings. Carbon taxes plus dividends would be globally progressive, even without international transfers. My approach to estimating the consumer incidence of carbon pricing uses bilateral trade data and features non-homothetic consumers who differ both between and within countries. The supply side includes substitution of inputs along global value chains.

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1. Introduction

Governments around the world are introducing prices on carbon dioxide (CO_2) emissions. In 2005, when the European Union launched its Emissions Trading Scheme (ETS), less than 5% of global greenhouse gas emissions were subject to a price. In 2020, price coverage is expected to exceed 20% with the launch of China's permit scheme (World Bank and Ecofys, 2018). A price on carbon emissions pushes consumers to buy less emissions-intensive goods and producers to use cleaner inputs. But it also has a cost, especially to consumers who may see prices rise. In this article, I estimate the global distribution of that cost to consumers due to higher prices. I show that the consumer cost of carbon pricing is globally regressive—it disproportionally affects poorer consumers—and more so between than within countries.

I estimate for the first time how the consumer cost of carbon pricing is distributed globally—both between many countries and at different income levels within them. Between countries, the consumer cost is shaped by differences in the composition of aggregate consumption and the fossil-fuel-intensity of production—consumers in countries that rely heavily on fossil fuel inputs face higher costs. Within countries, consumption baskets vary with income and so do consumer costs. Since truly multilateral climate policy was often deemed unlikely (e.g. Poterba, 1993), the tax incidence literature has largely focused on the within-country incidence of unilateral climate policy. But even coordinated domestic climate policy, as envisioned by the Paris Agreement signed in 2015, can have distributive effects across countries. This is particularly true considering that goods are often traded internationally and produced in globally connected value chains. The emergence of similar carbon pricing schemes around the world thus warrants a global approach to welfare analysis.

My approach complements research on other channels that shape the global welfare effects of climate policy. Importantly, we may wish to compare the cost of carbon pricing to the benefits of reduced climate damage. Recent evidence suggests that these benefits vary significantly across regions and may fall disproportionately to poor countries with high average temperatures (Burke et al., 2015; Nordhaus,

2017). By estimating how the consumer cost of carbon pricing is distributed globally, I contribute another element towards a more complete welfare analysis of climate policy. The results can shed light on who may be prone to resisting climate policy and inform the design of more equitable policy.

To estimate the global consumer incidence of carbon pricing, I combine structural models of demand and supply into a novel framework. On the demand side, I estimate a global demand system using data on bilateral trade of final goods between 40 countries and 35 industries from the World Input-Output Database (WIOD). Here, I build on work by Fajgelbaum and Khandelwal (2016) who propose a global Almost Ideal Demand System (AIDS) framework which can be parameterized using structural gravity equations. This model includes non-homothetic preferences—expenditure shares vary with income—which are essential to capture the incidence of carbon pricing within countries. Fajgelbaum and Khandelwal (2016) use their model to estimate the distribution of the gains from trade. My paper is the first to apply a non-homothetic gravity approach to the global incidence of carbon pricing.

On the supply side, I model substitution of intermediate inputs along global value chains. I also allow producers to substitute between primary fossil fuels used in production. Again, I use gravity equations to identify the relevant model parameters. I then simulate how a carbon price translates into changes in the structure of global production as emissions-intensive inputs become more expensive. Here, my approach is a static one, abstracting from the consequences of carbon pricing for factor incomes (Fullerton and Heutel, 2007; Rausch et al., 2011) and energy-saving technological innovation (Acemoglu et al., 2012a; Aghion et al., 2016). Nevertheless, the supply side adjustments that I do capture significantly mediate the cost increase to consumers and render my estimates more realistic. A naive extrapolation based on the emissions content of consumption, while ignoring supply side adjustments, would significantly over-estimate the consumer cost.

I estimate the global consumer incidence of three carbon pricing scenarios. The first is a global uniform carbon price as prescribed by economic theory on efficiency grounds. I show that the consumer cost due to higher prices, in absence of revenue recycling, would be highly regressive at the global scale. Consumers in the bottom half of the world income distribution suffer an equivalent variation welfare

loss more than twice as large as that of consumers in the top 10%. Importantly, I find that differences between countries are much more important than those within countries. Carbon pricing affects average consumers in poor countries more than poor consumers in average countries. For example, the cost is mildly regressive within the United States, equal to 1.2% of expenditures for consumers at the 10th percentile of the income distribution, and 1.0% at the 90th percentile. These within-country differences are dwarfed by comparisons to other countries, such as China, where the cost is 2.1% at the 10th percentile and 2.3% at the 90th percentile. Such differences between countries are due to the composition of aggregate consumption as well as the fossil-fuel-intensity of production.

Studies at the individual country level have shown that the incidence of any tax ultimately depends on how the collected revenue is used (Metcalf, 2009; Gonzalez, 2012). I find this to also hold true at the global level, when I allow national governments to use the carbon pricing revenue to finance per capita lump sum transfers. Such "carbon dividends" feature in many carbon pricing proposals, such as that proposed by the Climate Leadership Council for the United States[1]. Carbon dividends render the global uniform carbon price progressive—disproportionately benefiting low income consumers—both at the global scale and within most countries. No transfers between countries are needed to obtain this result.

A global uniform carbon price may not be likely anytime soon. I thus investigate two further scenarios that are highly policy relevant. As a second scenario, I assess the introduction of the EU ETS in 2005. Similar to the global carbon price, I find that the EU ETS is likely regressive across the 490 million European consumers and that this is largely driven by between-country differences—consumers in Eastern Europe and Baltic EU states are most affected. Finally, I investigate the consumer cost from introducing a carbon price on traded goods. Such Border Carbon Adjustments (BCA) are discussed as policy instruments to counter competitive pressures and carbon leakage under unilateral climate policy (see e.g. Fowlie et al., 2016). I find that complementing an EU-wide carbon price with BCA would most affect the poorest as well as the richest consumers in the EU. This time, the within-country variation in consumer cost dominates that between countries.

[1]The Climate Leadership Council's plan is available at `https://www.clcouncil.org/`.

This article contributes to three distinct literatures. First, it contributes to the literature on the incidence of environmental and energy taxes. Much of this literature is focused on the within-country incidence of domestic policies. Results suggest that the consumer cost of pricing carbon emissions (and related fuel taxes) is somewhat regressive—at least in rich countries such as the United States (Poterba, 1991; Grainger and Kolstad, 2010; Williams et al., 2015). However, these estimates vary with modelling choices and differ by country. In particular, energy taxes appear much less regressive, and sometimes neutral, when measures of permanent income are used (Fullerton, 2011) and when demand responses by consumers are taken into account (West and Williams, 2004). In addition, general equilibrium effects may be important. Rausch et al. (2011) find that changes in factor incomes, for example to land and capital, may alter the incidence of a carbon tax. Sterner (2012) summarizes the literature on the within-country incidence of taxing transport fuels and highlights that, while such policies appear regressive in some countries, they may well be progressive in others.

There are fewer contributions that explicitly estimate how the average consumer cost of carbon pricing differs between countries (early examples are Whalley and Wigle, 1991; Shah and Larsen, 1992), though such differences are often acknowledged in climate policy negotiations (e.g. Mehling et al., 2018). This article contributes to the literature by estimating the global consumer cost incidence of carbon pricing—both between and within many countries. In line with the literature on within-country incidence, I estimate that carbon pricing is regressive in some, mostly rich countries and progressive in some poorer ones. But I also find that differences between countries are much more important in shaping the global incidence. Finally, I find that the progressive nature of "carbon dividends" which has been documented at the country level also hold at the global scale.

Second, this article contributes to the literature on the design of EU climate policy. There is a large literature studying the design and effectiveness of the EU ETS introduced in 2005. The literature includes both *ex ante* and *ex post* evaluations (see surveys by Ellerman and Buchner, 2007; Martin et al., 2016). This article contributes to the literature by providing *ex ante* estimates of the EU ETS's consumer incidence across all 490 million EU residents. Further, it contributes to the

literature on carbon pricing targeted at traded goods. BCA can level the playing field by pricing the emissions content of imports that do not face a carbon price at home (Markusen, 1975; Hoel, 1996). There is a growing literature on the effectiveness of BCA in countering leakage (Böhringer et al., 2012; Fowlie et al., 2016) and their burden to different countries (Böhringer et al., 2018). Despite their theoretical appeal, there is to date scarce evidence on how the consumer cost of BCA is distributed within countries. My model distinguishes between the demand for domestic goods and import goods from different origins. It is thus uniquely suited to estimate how the cost of BCA is distributed across consumers. This article then contributes to the literature by providing the first estimate of the consumer incidence of BCA to complement an EU-wide carbon price.

Third, this article adds to a growing literature applying structural gravity approaches to environmental policy analysis. For example, Shapiro (2016) uses such an approach to characterise the CO_2 content of international shipping. Larch and Wanner (2017) simulate the trade and aggregate welfare effects of carbon tariffs. Finally, Caron and Fally (2018) use a gravity approach to demonstrate the role of country-level income in shaping the CO_2-content of aggregate consumption. In this article, I demonstrate that the structural gravity approach can be useful in answering a different question—by estimating how the consumer cost of carbon pricing is distributed globally. The structural gravity approach adopted in this and other papers represents a middle-ground between general equilibrium models and partial equilibrium approaches using detailed micro-data. General equilibrium analyses can capture a large number of adjustment margins and complex interactions, but often focus on a single representative consumer. In contrast, my framework allows for greater heterogeneity of consumers—both between and within countries. Another approach to incidence analysis relies on detailed micro-data from consumption surveys, but usually focuses on single countries. In contrast, my approach captures the consumer cost at a global scale within a unified framework. My framework can in principle be applied to any set of exogenous price changes. It is best suited for analyses at the global scale that involve international trade and make use of environmentally extended input-output methods.

2. Modeling the global cost of carbon pricing

I estimate within a unified framework how the consumer cost of carbon pricing is distributed globally—both between countries and at different income levels within countries. My simple model of the global economy captures both adjustments on the demand side—consumers react to higher final goods prices—and adjustments on the supply side—producers substitute away from carbon-intensive inputs. In this section, I describe the theoretical framework. In the next section, I explain how I estimate model parameters using data on bilateral trade flows.

2.1. Demand: A global Almost Ideal Demand System

The core of my analysis is a global Almost Ideal Demand System (AIDS) describing consumer preferences. Importantly, it allows for non-homothetic preferences—consumers at different income levels within countries differ in their demand for emissions-intensive goods, which means they differ in their exposure to carbon pricing. AIDS was first proposed by Deaton and Muellbauer (1980) and is characterized as follows.

Assumption A1 (AIDS Consumer Preferences) *Demand of consumer h for good j is characterized by the family of log price-independent generalized (PIGLOG) preferences proposed by Muellbauer (1975) with indirect utility:*

$$v(x_h, \mathbf{p}) = F\left[\left(\frac{x_h}{a(\mathbf{p})}\right)^{\frac{1}{b(\mathbf{p})}}\right] \tag{1}$$

$F(.)$ is increasing and well-behaved, and the price aggregators are:

$$a(\mathbf{p}) = \exp\left(\underline{\alpha} + \sum_{j=1}^{J} \alpha_j \log p_j + \frac{1}{2}\sum_{j=1}^{J}\sum_{k=1}^{J} \gamma_{jk} \log p_j \log p_k\right) \tag{2}$$

$$b(\mathbf{p}) = \exp\left(\sum_{j=1}^{J} \beta_j \log p_j\right) \tag{3}$$

A consumer h chooses between J goods and has indirect utility $v(x_h, \mathbf{p})$ which depends on her total expenditure budget x_h and the vector of prices $\mathbf{p}$. The additional assumptions on price aggregators $a(\mathbf{p})$ and $b(\mathbf{p})$ close the description of the AIDS model. Consumer h devotes the following share of her expenditures to good j:

$$s_j(\mathbf{p}, x_h) = \frac{x_{jh}}{x_h} = \alpha_j + \sum_{k=1}^{J} \gamma_{jk} \log p_k + \beta_j \log\left(\frac{x_h}{a(\mathbf{p})}\right) \tag{4}$$

Expenditure of h on good j depends on preferences for good j (α_j), prices of all goods k (p_k) and individual real income ($\frac{x_h}{a(\mathbf{p})}$). Key elasticities are the cross-price elasticities between goods j and k (γ_{jk}) and income (semi)-elasticities for each good j (β_j). Positive good-specific income elasticities ($\beta_j > 0$) mean that j is a luxury good (and a necessity if $\beta_j < 0$). Parameters are restricted to $\sum_{j=1}^{J} \alpha_j = 1$, $\sum_{j=1}^{J} \beta_j = \sum_{j=1}^{J} \gamma_{jk} = 0$ and $\gamma_{jk} = \gamma_{jk}$ for all j, k. While allowing for heterogeneity of expenditure patterns across the income distribution, these expenditure shares are still conveniently aggregated via an inequality-adjusted version of average income. The aggregate share that all consumers spend on good j is:

$$S_j = \alpha_j + \sum_{k=1}^{J} \gamma_{jk} \log p_k + \beta_j y \tag{5}$$

Aggregate expenditure shares resemble individual ones, but individual income is replaced by inequality adjusted real income $y = \log\left(\frac{\tilde{x}}{a(\mathbf{p})}\right)$. This is the price-adjusted version of the inequality-adjusted mean expenditure $\tilde{x} = \bar{x}e^{\Sigma}$ where $\Sigma = \left[\frac{x_h}{\bar{x}} \log\left(\frac{x_h}{\bar{x}}\right)\right]$ is the Theil index of income inequality.

Thanks to this aggregation property, it is possible to estimate demand parameters from aggregate expenditure shares. In Section 3, I explain how I do so using between-country trade flows, following closely the method proposed by Fajgelbaum and Khandelwal (2016). Once parameterized, the demand system allows for simulation of the consumption distribution within each country around aggregate expenditure levels. Specifically, I allow average preferences for goods j (α_j) to differ between countries, but assume that consumers in all countries share the same price and income elasticities (γ_{jk} and β_j).

For each carbon pricing scenario, I simulate the welfare effect to consumers at different income levels in each country. I consider the Hicksian equivalent variation, which represents the maximum amount of income that a consumer would give up for a price increase not to occur. Keeping to the notation of Fajgelbaum and Khandelwal (2016), this welfare effect is:

Proposition 1 (Welfare Effect) *The marginal welfare effect of a small change in (log) prices, $\hat{p}_j = dlog(p_j)$ on consumer h consuming goods j is:*

$$\begin{aligned} \hat{\omega}_h = \sum_{s=1}^{S} \left(-\hat{p}_j\right) S_j \quad & - \left(\sum_{s=1}^{S} \beta_j \hat{p}_j \right) \log\left(\frac{x_h}{\tilde{x}}\right) \quad + \hat{x}_h \\ = \hat{W} \quad & + \hat{\psi}_h \quad + 0 \end{aligned} \tag{6}$$

Proof. See Appendix 1, following Fajgelbaum and Khandelwal (2016). ■

The cost from higher prices can be separated into an aggregate cost common to all consumers (in a country), $\hat{W}$, and an individual cost to consumer h, $\hat{\psi}_h$. The individual cost $\hat{\psi}_h$ is a function of h's income (x_h) relative to the country's inequality-adjusted mean income ($\tilde{x}$). It represents differences in expenditure composition from the average (driven by income elasticities β_j). Finally, $\hat{x}_h$ is the change in (log) income of h. Besides a possible carbon dividend to recycle carbon pricing revenue, I assume that incomes are unaffected by climate policy ($\hat{x}_h = 0$)[2]. For non-marginal changes in prices $\hat{\mathbf{p}}$, equation (6) is integrated over taking into account changes in expenditure patterns as well as constraining budgets shares to remain between 0 and 1.

Below, I parameterize a global version of this demand system using data on bilateral trade flows by pairing the AIDS structure with the assumption of national product differentiation by country of origin (Armington, 1969). Each sector s from country i sells a different product variety (so that $J = S \times I$). This approach follows Fajgelbaum and Khandelwal (2016) who use it to estimate the distribution of the gains from trade (relative to counterfactual autarky). Using such a framework to estimate the global incidence of carbon pricing is one contribution of this article.

[2]There is evidence that the incidence of environmental policy may be altered when considering changes to factor incomes, including wages (Fullerton and Heutel, 2007, 2010; Rausch et al., 2011). However, in this paper I focus on the global distribution of costs on the "use side".

2.2. Supply: Intermediate inputs in global value chains

Consumers are not the only ones affected by carbon pricing. Producers will see changes in the cost of inputs and will move away from emissions-intensive inputs. This will in turn reduce the amount of emissions embodied in final goods and somewhat soften the effect on consumers. I allow for such substitution of both intermediate and primary inputs. Substitution of primary inputs—in the form of fossil fuel combustion—is discussed further below. In this section, I derive a simple model of global value chains which allows for intermediate input substitution and remains consistent with commonly used methods of input-output based emissions accounting. The supply side is characterized by a set of Constant Elasticity of Substitution (CES) production functions. These can again be parameterized using a structural gravity approach—this time using data on inter-industry trade flows.

Assumption A2 (CES Production Functions) *Assume that all producers in each sector k have an identical Constant Elasticity of Substitution (CES) production function across J intermediate inputs with prices ϕ_{jk}. We further assume perfect competition and constant returns to scale in all sectors. Input choices in each sector are then equivalent to a representative producer minimizing input cost C_k:*

$$min\ C_k = \sum_j \phi_{jk} f_{jk} \quad s.t.\ T_k \left(\sum_j a_{jk}^{1/\sigma_k} f_{jk}^{(\sigma_k-1)/\sigma_k} \right)^{\sigma_k/(\sigma_k-1)} = X_k \tag{7}$$

For any level of output X_k, producers minimize input costs C_k. The expenditure share on input j among expenditures for all intermediate inputs is given by:

$$S_{jk} = \frac{\phi_{jk} f_{jk}}{C_k} = a_{jk} \phi_{jk}^{(1-\sigma_k)} P_k^{(\sigma_k-1)} \tag{8}$$

The expenditure share of on input j is decreasing in its price ϕ_{jk} relative to the input price index of sector k, $P_k = (\sum_j a_{jk} \phi_{jk}^{(1-\sigma_k)})^{1/(1-\sigma_k)}$. Constant returns to scale combined with perfect competition imply that input shares and output prices are independent of final demand. No equilibrium price condition is needed.

Below, I discuss how I estimate the relevant substitution elasticity σ_k using a structural gravity approach based on bilateral inter-industry trade flows between

pairs of 1400 ($K = J = 40$ countries $\times$ 35 sectors) sectors. These come from the World Input-Output Database (WIOD), which is one of the most commonly used multi-regional input-output (MRIO) databases[3]. Once parameterized, I simulate input substitution in response to carbon pricing and approximate the new equilibrium input-output structure of the economy. These supply side dynamics render the welfare analysis more realistic, as we may expect significant adjustments to occur before products reach final consumers.

2.3. Supply: Accounting for emissions along value chains

To model the impact of input substitution on final prices, I model adjustments in global input-output linkages—the structure of global value chains. The importance of accounting for the structure of production has previously been demonstrated by Caliendo and Parro (2015) in the context of estimating the welfare effects of NAFTA tariff reductions. My approach allows me to model adjustments in value chains due to input substitution and use MRIO-based methods of emissions accounting to estimate changes in final goods prices. These are frequently used to characterize the indirect emissions embodied in consumption (e.g. Levinson and O'Brien, 2019; Sager, 2019). The above CES production technologies translate into the input-output framework as follows.

Total expenditure on all intermediates by sector k is $C_k = P_k X_k$. The difference between the final price p_k for one unit of good k and required input expenditures defines the value added share $\kappa_k = \frac{p_k - P_k}{p_k}$. Each dollar value of output in sector k then uses an average amount of dollar value inputs from sectors j, $c_{jk} = S_{jk}(1 - \kappa_k)$. All output is used either as intermediate input in another sector or as final consumption, both at the same price. This yields a linear relation between input and output in value terms:

$$\mathbf{x} = \mathbf{C}\mathbf{x} + \mathbf{y} \tag{9}$$

[3]One limitation of using WIOD data is that I cover only 35 sectors of the economy. As such, I will be able to estimate and simulate substitution between inputs from these 35 sectors. I do not capture substitution of intermediate goods within sectors as more fine-grained analyses might (as e.g. Levinson, 2009, who distinguishes 450 manufacturing industries in the US). However, WIOD is one of the few sources for harmonized multi-regional input-output (MRIO) accounts and substitution between the 35 sectors should already capture a significant portion of input substitution.

Here, $\mathbf{x}$ is the K-vector of aggregate outputs in value terms (elements $p_k X_k$), $\mathbf{C}$ is the $(K \times K)$-matrix of normalized input requirements c_{jk} and $\mathbf{y}$ the K-vector of final consumption again in value terms (elements $p_k y_k$). While this linear relationship follows Leontief (1970), it does not require Leontief production technologies. The notable difference is that under CES technologies the relationship is expressed in value terms instead of volume. This is similar to Acemoglu et al. (2012b), who use such a linear mapping to describe the network structure of an economy with Cobb-Douglas technologies[4].

The Direct Requirement matrix $\mathbf{C}$ has element c_{jk} which is the dollar amount of intermediate input from industry j necessary for the production of a dollar of output in industry k. Following Leontief (1970), the Total Requirement matrix $\mathbf{T}$ is:

$$\mathbf{x} = [\mathbf{I} - \mathbf{C}]^{-1}\mathbf{y} = \mathbf{T}\mathbf{y} \tag{10}$$

Elements of $\mathbf{T}$, t_{jk}, describe the dollar amount of total input from sector j embedded in a dollar of final consumption from sector k, accounting for all upstream processes. Total input requirements are then translated into total emissions intensities:

$$\mathbf{e} = \mathbf{T}'\mathbf{d} \tag{11}$$

The J-vector $\mathbf{d}$ of direct emissions intensities δ_j describes for each sector the CO_2 emissions per dollar output. Element ε_k of $\mathbf{e}$ then summarizes the total CO_2 emissions intensity (tons of CO_2 per \$) of final consumption from sector k, including all upstream emissions in sectors j. The effect on final prices due to a price on carbon emissions will be a function of these total emission intensities ε_k. When evaluating carbon pricing scenarios, I simulate a new equilibrium input-output structure of the economy ($\mathbf{C}$ and $\mathbf{T}$), which yields a new set of emissions intensities ($\mathbf{e}$). These directly translate into final price changes seen by consumers.

[4]When technologies are of the Cobb-Douglas variety, C is constant for all price combinations (as in Acemoglu et al., 2012b, and others). I add further flexibility in input substitution by modeling CES technologies, which means that C adjusts when input prices change. This reduces analytical tractability, but adds what I think is important flexibility when analyzing carbon pricing. I approximate the adjustment of inputs recursively as described in Appendix C.

2.4. Supply: Price dynamics

For any given input-output structure, the emission intensity ε_k of final good k determines its relative price increase when we introduce a price on CO_2 emissions. When no input substitution takes place, this takes the following form[5].

Proposition 2 (Price effect without substitution) *Assume a carbon price τ (in \$ per ton of CO_2) is introduced. Holding constant the structure of value chains* $\mathbf{C}$ *and hence the total emissions content of goods ε_k, this will raise final prices to a new level $p_k^{new} = (1+\tau\varepsilon_k)p_k$.*

This is the price increase predicted by standard MRIO methods that assume fixed proportion production functions (following Leontief, 1970). But I allow producers to substitute intermediate inputs. This alters the structure of value chains and, consequently, emissions intensities ε_k. This invites yet further adjustments to inputs until a new equilibrium is reached. I also allow carbon prices to differ between goods j.

Proposition 3 (Price effect with input substitution) *Assume a set of carbon prices $\{\tau_{jk}\}$ on intermediate goods j used in production k is introduced. Given initial input requirements $\{c_{jk}\}$ and direct emissions intensities $\{\delta_j\}$, the new equilibrium production structure is defined jointly by:*

$$c_{jk}^{new} = c_{jk}\left(\frac{(\sum_i a_i(1+\tau_{ik}\varepsilon_i^{new})^{(1-\sigma_k)})^{1/(1-\sigma_k)}}{1+\tau_{jk}\varepsilon_j^{new}}\right)^{\sigma_k} \quad \forall k,j \tag{12}$$

$$\mathbf{e}^{new} = \left[(\mathbf{I}-\mathbf{C}^{new})^{-1}\right]'\mathbf{d} \tag{13}$$

Proof. See Appendix B. ■

The procedure yields a new set of final goods prices, which consumers face under carbon pricing. For each carbon pricing scenario, I approximate numerically the new equilibrium supply chain structure $\mathbf{C}^{new}$, emission intensities ε_k^{new} and prices p_k^{new}. The procedure is described in Appendix C.

[5] It is does not matter where in the supply chain the price on emissions is levied. This could be a consumption tax levied on the final good or emissions pricing at the source. Perfect competition implies that producers will fully pass-through price increases to consumers and competitive firms will internalise carbon prices even if they were to be levied at the point of sale.

2.5. Supply: Fuel switching

As described above, producers react to carbon pricing by reducing the share of CO_2 intensive intermediate inputs. But of course, producers may also reduce emissions that are directly generated by their own production processes.

To model fuel switching, I exploit the dual structure WIOD. Input-output tables capture all transactions between sectors in value terms and are ideally suited to trace the flow of intermediate goods. In addition, WIOD environmental satellite accounts provide information on CO_2 emissions by sector and energy commodity. They capture emissions only in that sector where they occur, i.e. where fossil fuel is combusted (Genty et al., 2012). I use this two-tier reporting of transactions in value terms and emissions where they occur to separate switching of intermediate inputs and substitution of direct fossil fuel inputs. Before modeling adjustments in intermediate inputs $\mathbf{C}$ and thus total emissions intensities ε_k, I allow producers to adjust the mix of primary fossil fuel inputs. This alters direct emission intensities δ_k, which then feed into the adjustment of value chains.

Specifically, I assume that each unit of output is produced by combining energy services with intermediate inputs. I assume that these energy services follow a constant elasticity of substitution (CES) production function using three fuel inputs—coal, oil and gas[6]. Again, the representative producer in industry k minimizes direct input costs of fuels for a given level of energy services output. Analytically, this is identical to intermediate input choice in (8).

The key assumption is that the total amount of energy services needed to produce one unit of output in each sector remains the same. But producers can shift between the fossil fuels used to generate energy services. In all simulations, the most important instance of fuel switching occurs in the electricity sector, where gas is substituted for coal when carbon is priced. This reduces the direct emission intensity (δ_k^{new}) of the electricity sector and in turn lowers the indirect emission intensities (ε_k^{new}) of all downstream sectors that use electricity.

[6]I use WIOD data on energy-related emissions in three fuel groups: coal, oil and gas. Coal: anthracite, lignite and coke; Oil: gasoline, Diesel, jet kerosene, LFO, HFO and naphtha; Gas: natural and other gas.

3. Estimating model parameters

To calibrate the above models of demand and supply, I use data on bilateral trade flows between 40 countries and 35 sectors from the World Input-Output Database (WIOD). These provide yearly cross-sections between 1996 and 2009. I identify the demand parameters using data on bilateral trade of final goods and production function parameters using data on bilateral inter-industry trade.

3.1. Demand: Estimating demand system parameters

To identify demand parameters, I follow Fajgelbaum and Khandelwal (2016) in embedding the AIDS demand structure in a multi-sector Armington model of international trade of final goods, allowing for goods within each sector to be differentiated by origin and for cross-country differences in sectoral productivity and trade cost. Essentially, each sector from each country sells a different variety. In WIOD, this translates into 1400 varieties ($K = J = 40 \times 35$).

Consumers in destination country n consume goods from sector s in origin i. To characterize demand responses and welfare effects for households h in country n, I estimate income semi-elasticities (β_i^s) for each of the 1400 varieties, as well as price elasticities. For the latter, I follow Fajgelbaum and Khandelwal (2016) in assuming that there is symmetric substitution within each sector s between goods from different countries i, but no substitution between sectors:

$$\gamma_{ii'}^{ss'} = \begin{cases} -\left(1-\frac{1}{N}\right)\gamma^s & \text{if } i = i' \text{ and } s = s' \\ \frac{1}{N}\gamma^s & \text{if } i \neq i' \text{ and } s = s' \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

Consumers can substitute textiles from the United States with textiles from India, but they cannot substitute textiles with minerals. To identify the 35 sector-level price elasticity parameters (γ^s), I assume that trade costs between country-pairs (t_{ni}) are of the iceberg variety, implying $\frac{p_{ni}^s}{p_i^s} = t_{ni}$.

Specifically, I assume that bilateral trade costs between origin i and destination n are $t_{ni} = d^{\rho}\prod_l \left(g_{l,ni}^{\delta_l}\right)\eta_{ni}$, where d_{ni} is distance and ρ is the distance elasticity

of trade costs. Other determinants of bilateral gravity are in $g_{l,ni}$. Following Fajgelbaum and Khandelwal (2016), this yields an estimating equation for aggregate expenditure by consumers in country n on goods from sector s and country i:

$$S_{ni}^s = \frac{Y_i^s}{Y_W} + \alpha_i(S_n^s - S_W^s) - (\gamma^s \rho^s) D_{ni} + \sum_j (\gamma^s \delta_j^s) G_{j,ni} + (\beta_i^s - \alpha_i \overline{\beta}^s)\Omega_n + \varepsilon_{ni}^s \quad (15)$$

These aggregate expenditure shares (S_{ni}^s) are observed in WIOD. Consumers in n buy more goods from sector s in origin country i if that sector is a large relative to the world economy ($\frac{Y_i^s}{Y_W}$) and if consumers in n spend more on goods in sector s relative to the rest of the world ($(S_n^s - S_W^s)$). Variation in trade costs helps identify price elasticities (γ^s). If trade is more concentrated among less distant country pairs within one sector than another, I estimate the former to face a higher price elasticity of demand. As proxies for bilateral trade cost, I use data from CEPII's Gravity database on the distance between country pairs (D_{ni}), as well as indicators for common language and a shared border ($G_{j,ni}$).

Variation in the inequality-adjusted mean income of country n relative to the world ($\Omega_n = y_n - \overline{y}_W$) helps identify the income elasticities (β_i^s). If textiles from the United States are consumed more in richer countries, or more unequal countries, than textiles from India, then I estimate the former to have a higher income elasticity. Ω_n is calculated using country-level population and income (GDP) from the Penn World Tables and the Gini index of income inequality from the World Income Inequality Database (WIID). I assume that individual expenditure x_h is proportional to income, i.e. that there is a constant savings rate[7]. Assuming a log normal income distribution, the Gini index is easily converted into the required Theil index[8]. Following the methodology of Fajgelbaum and Khandelwal (2016), I also proxy for the non-homothetic price index $a(\mathbf{p})$ with a Stone price index for each destination country n using quality-adjusted prices as provided by Feenstra and Romalis (2014).

From the estimation of (15), I identify the following parameter estimates: $\hat{\alpha}_i$,

[7] Basing my analysis on expenditure distributions—sometimes seen as more representative of lifetime income—should make it less likely to find regressive effects of carbon pricing than using annual income (as shown e.g. by Hassett et al., 2009; Grainger and Kolstad, 2010).

[8] Assuming a log-normal distribution of expenditure with variance σ^2, the Theil index is $\sum = \frac{\sigma^2}{2}$ where the relation between σ^2 and the Gini coefficient G is given by $\sigma^2 = 2\left[\frac{G+1}{2}\right]^2$.

$\widehat{(\beta_i^s - \alpha_i \overline{\beta}^s)}$, $\widehat{(\gamma^s \rho^s)}$. A second estimation equation helps to identify the missing parameters $\hat{\overline{\beta}}^s$. I estimate an Engel curve projecting aggregate expenditure shares in country n for sectors s on the inequality-adjusted real income y_n:

$$S_n^s = \alpha^s + \overline{\beta}^s y_n + \varepsilon_n^s \tag{16}$$

This estimation helps to identify what Fajgelbaum and Khandelwal (2016) call the "sectoral betas", the sector average income semi-elasticities, $\overline{\beta}^s$. ε_n^s is the specific taste of importer n for sector s. These estimates $\hat{\overline{\beta}}^s$ together with the estimates of $\hat{\alpha}_i$ from the above gravity estimation are sufficient to identify origin-sector specific income semi-elasticities $\hat{\beta}_i^s$. Finally, to pin down price elasticity parameters $\hat{\gamma}^s$, I follow Novy (2013) (and Fajgelbaum and Khandelwal, 2016) in setting $\rho^s = \rho = 0.177$ for all s.

3.2. Supply: Estimating production function parameters

On the supply side, I again identify the relevant model parameters from trade data—this time from bilateral inter-industry trade. I again derive a simple gravity equation to estimate the production elasticity σ_k for each industry k. The above CES production function implies that producers in industry k spend the following share of their expenditures on intermediate inputs from industry j:

$$S_{jk} = \frac{\phi_{jk} f_{jk}}{P_k X_k} = a_{jk} \phi_{jk}^{(1-\sigma_k)} P_k^{(\sigma_k - 1)} \tag{17}$$

I consider bilateral inter-industry trade flows between 1.96m (1400^2) industry pairs—destination sector k in country n from origin sector s in country i. Again, I assume that each sector s in origin i produces a distinct input variety ($J = S \times I$) and that the market for intermediate goods is perfectly competitive. I further assume that prices are the same for goods from sector s whether they are used as intermediates or final goods ($p_i^s = \phi_i^s$) and that traded goods are subject to iceberg trade costs t_{ni} between destination n and origin i, $p_{ni}^s = t_{ni} p_i^s$. Finally, I assume that production functions are identical for each destination sector k across countries n ($\sigma_{n,k} = \sigma_k$

and $a_{ni}^{ks} = a_i^{ks}, \ \forall n$). Each sector k in destination n will then spend the following share on intermediate inputs from sector s in origin i:

$$S_{ni}^{ks} = a_i^{ks}(t_{ni})^{(1-\sigma_k)}(p_i^s)^{(1-\sigma_k)}(P_n^k)^{(\sigma_k-1)} \tag{18}$$

In its log-linear version, we obtain the following gravity equation:

$$\begin{aligned}\log\left(S_{ni}^{ks}\right) &= \log\left(a_i^{ks}\right) + (1-\sigma_k)\log\left(t_{ni}\right) + (1-\sigma_k)\log\left(p_i^s\right) - (1-\sigma_k)\log\left(P_n^k\right) \\ &= (1-\sigma_k)\log\left(t_{ni}\right) + \lambda_n^k + \omega_i^s\end{aligned} \tag{19}$$

This gravity equation is very similar to that proposed by Anderson (1979) and Anderson and Van Wincoop (2003) to model gravity for demand of consumers with CES preferences[9]. Instead, I estimate the sector-specific CES production elasticities σ_k. Again, I identify σ_k using cross-sectional variation in bilateral trade costs t_{ni} and assume that $t_{ni} = d_{ni}^{\rho}\Pi_l\left(g_{l,ni}^{\delta_l}\right)\eta_{ni}^{ks}$, where d_{ni} is distance, ρ is the distance elasticity of trade costs, and $g_{l,ni}$ are other gravity variables. The final estimating equation is:

$$\log\left(S_{ni}^{ks}\right) = (1-\sigma_k)\rho\log\left(d_{ni}\right) + \sum_l\left[(1-\sigma_k)\delta_l\log G_{l,ni}\right] + \lambda_n^k + \omega_i^s + \varepsilon_{ni}^{ks} \tag{20}$$

Again, I obtain data on the bilateral distance between country pairs (d_{ni}) from CEPII. The other elements of $G_{l,ni}$ are indicators for common language and a shared border, also from CEPII. I estimate this equation separately for the 35 industries k[10].

[9] Anderson and Van Wincoop (2003) use market clearing conditions and symmetry assumptions to transform equation (18) into a gravity equation as a function of equilibrium price indices, or "multilateral resistance". I replace multilateral resistance terms with fixed origin and destination fixed-effects as is commonly done. As such my estimates are consistent with alternative derivations of gravity equations which result in a multiplicative form of bilateral resistance.

[10] For estimation, I apply an ordinary least squares (OLS) estimator with origin (country-sector) and destination (country-sector) fixed-effects. This has been shown to be consistent (e.g. Head and Mayer, 2014). I again assume that $\rho = 0.177$.

3.3. Model overview and parameter estimates

Table 1 provides an overview of the framework used here. The key advantage is that it makes possible welfare analysis across consumers in different countries and at different income levels within countries. This is done by modeling consumer preferences within an AIDS framework, which allows for non-homothetic preferences captured by the 1400 origin-sector specific income semi-elasticities (β_i^s) identified from between-country variation in aggregate expenditure shares. The demand structure also allows consumers to substitute away from dirty goods when they become more expensive. This is captured by the 35 price elasticity parameters (γ^s) identified from variation in bilateral trade cost. Both income and price elasticities of demand are estimated from equations (15) and (16) using WIOD data on bilateral final goods trade following Fajgelbaum and Khandelwal (2016).

On the supply side, I model production in each sector by a separate Constant Elasticity of Substitution (CES) production function using intermediate inputs. This allows producers to substitute away from dirty intermediate goods when prices rise. I also allow producers to reduce emissions in their production process directly by substituting between the three primary fossil fuel groups—coal, gas and oil. Gravity equation (20) yields estimates of the 35 CES production elasticities (σ_k). These are estimated from data on inter-industry trade flows and again identified from variation in bilateral trade cost. Appendix D provides an overview of parameter estimates. Estimates are highly consistent across different years[11].

The relative importance of the different adjustment margins of demand and supply is demonstrated using counterfactual carbon pricing scenarios. Figure 1 summarizes the predicted potential for global CO_2 emissions reductions under different levels of a global uniform carbon price. This price applies to all goods, traded and non-traded. I use 2004 as a base year as it was before any major carbon pricing scheme had been introduced in any of the 40 countries. In the year 2004, we start out with 20.4 Gt of total CO_2 emissions in the 40 WIOD countries[12]. The predicted

[11] For example, I consistently estimate agriculture to be a necessity ($\hat{\beta}_s < 0$) and real estate services to be a luxury good ($\hat{\beta}_s > 0$). Within sectors, varieties from the United States and Japan appear more likely to be luxury goods, while varieties from India and Indonesia are necessities.

[12] This amount may differ from other aggregate emissions numbers for various reasons. Most importantly, WIOD only covers 40 countries and environmental satellite accounts do not include

Table 1: Method overview

	Theory	Parameters	Data
Demand	AIDS preferences (non-homothetic)	Income elast. (β_i^s) Price elast. (γ^s)	WIOD: final goods trade (35 sectors, 40 countries)
Supply: Input substitution	CES production (per sector)	CES elast. (σ_k)	WIOD: inter-industry trade (35 sectors, 40 countries)
Supply: Fuel switching	CES production (per sector)	CES elast. (σ_k)	WIOD: fossil-fuel shares (coal, gas, oil)

Notes: Overview of the key model characteristics and data sources.

emissions reduction from demand responses is limited. At a carbon price of 30 USD/t, total emissions would be reduced by 2.5 Gt to 17.9 Gt by demand response alone (blue, dashed line). This reduction is mostly due consumers substituting away from emissions-intensive goods. A small portion is due to reduced spending power from across the board price increases.

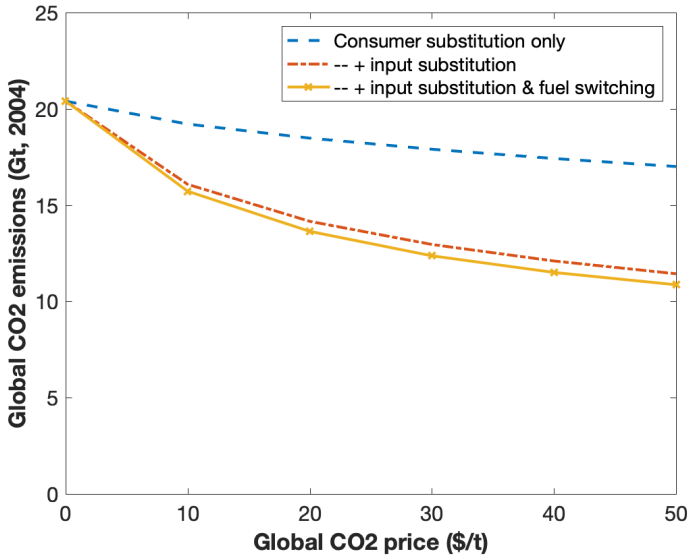
Allowing for substitution of intermediate inputs increases the emissions reduction potential of carbon prices. At a global carbon price of 30 USD/t, input substitution adds a further 4.9 Gt in annual emissions reductions (red, dash-dotted line). Finally, fuel switching adds a further 0.6 Gt in annual emissions reductions (yellow, solid line). For the rest of this article, I allow for fuel switching and input substitution before carbon prices are passed on to consumers.

These supply-side dynamics significantly mitigate the price increase passed on to consumers and render the incidence estimates more realistic. Nevertheless, I exclude some margins of adjustment that may be important. I assume perfect competition and thus can model neither the possibility of imperfect pass-through of carbon prices (Ganapati et al., 2019), nor the potential for competitive price adjustments in the market for fossil fuels. While I allow for fossil fuel switching, I ignore the potential to replace fossil fuels with renewable energy sources. My model is static and assumes a constant technologies in production, both across intermediate and fossil fuel inputs. This means that I exclude the possibility that carbon pricing induces energy-saving innovation in production (Aghion et al., 2016). I also ignore

emissions from land conversion.

the possible repercussions for factor incomes to households (Rausch et al., 2011). Each of these dynamics may bias the results presented in this article as long as any such adjustment systematically falls on either richer or poorer consumers. Finally, I estimate the consumer cost due to higher prices only. Ultimately, the welfare effects of carbon pricing might be mitigated through the redistribution of collected revenue in the form of income tax cuts or lump-sum transfers (West and Williams, 2004). In additional scenarios, I thus allow for redistribution of the revenue from carbon pricing by means of lump sum transfers, so-called "carbon dividends".

Figure 1: Global price - Global CO_2 emissions



Notes: This figure shows global aggregate CO_2 emissions under different levels of a global uniform carbon price in USD per ton of CO_2 simulated in 2004 (WIOD, 40 countries, 35 sectors). Different lines allow for different margins of adjustment in the model: 'No substitution' refers to demand adjustments only with a fixed supply structure; 'input substitution' refers to demand adjustments plus intermediate input substitution by producers; 'input + fuel substitution' refers to the full model allowing for demand adjustments plus intermediate input substitution as well as fuel switching by producers.

4. The global consumer cost of carbon pricing

Once calibrated, I use my framework to estimate the gobal consumer cost under three carbon pricing scenarios. First, I simulate a world where all 40 countries implement a uniform price on carbon emissions. This is what economic theory may suggest based on efficiency grounds to meet the global climate externality. I use 2004 as a baseline year, as it is before the introduction of the first large-scale carbon pricing scheme—the EU Emissions Trading Scheme (ETS). While a global uniform price may not be realistic anytime soon, this EU-wide carbon price already exists. The second scenario is thus the introduction of the EU ETS in 2005. Finally, I simulate a policy of complementing an EU-wide carbon price with Border Carbon Adjustments (BCA) that target the emissions content of imported goods.

4.1. A global uniform carbon price

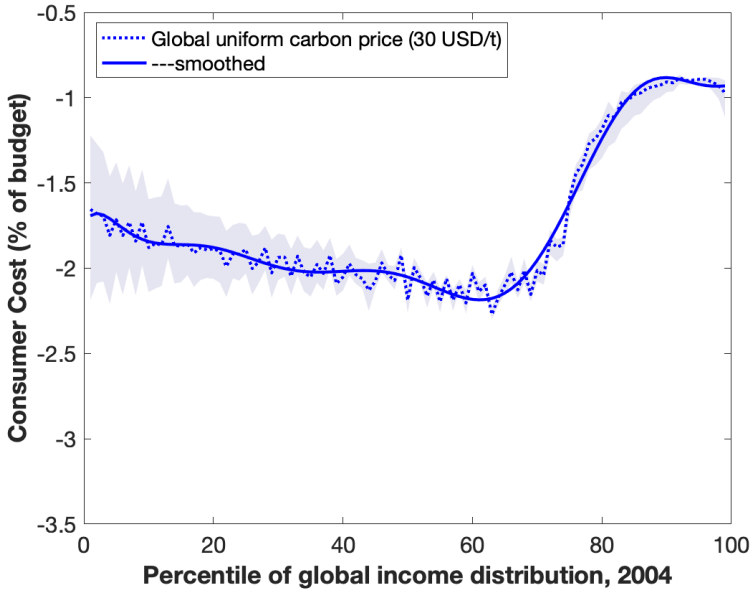
I estimate the consumer cost from a global uniform carbon price of 30 USD/t[13]. Figure 2 shows how the resulting consumer cost is distributed across the global income distribution. The horizontal axis represents percentiles of the income distribution of the ca. 4.2 Billion residents living in the 40 WIOD countries in 2004. The dashed line shows estimates for the average consumer cost as a share of annual expenditure for each percentile. More negative values represent a higher cost. The solid line shows a 10th degree polynomial approximation thereof. The blue band represents 95% confidence intervals[14]. The first insight here is that a global carbon price is rather regressive at a global scale. The cost to consumers in the bottom half of the world income distribution—equivalent to them loosing 1.8% to 2.2% of their annual income—is more than twice as large as that of consumers in the top 10 %.

A second insight is that the incidence differs between countries. Figure 3 shows the consumer cost in each of the 40 countries, at different percentiles of the country income distributions. Upward-sloping lines suggest that carbon pricing is

[13] Some may argue that a carbon price of 30 USD/t of CO_2 is low compared to estimates of the climate externality. I show in Appendix G that, while the overall cost is higher, the relative incidence of a carbon price of 100 USD/t is similar to the results reported here for 30 USD/t.

[14] Confidence intervals are from 500 separate simulations, each using a different set of model parameters drawn from the joint normal distributions from estimations (15), (16) and (20).

Figure 2: Global price of 30 USD/t - Global distribution of consumer cost



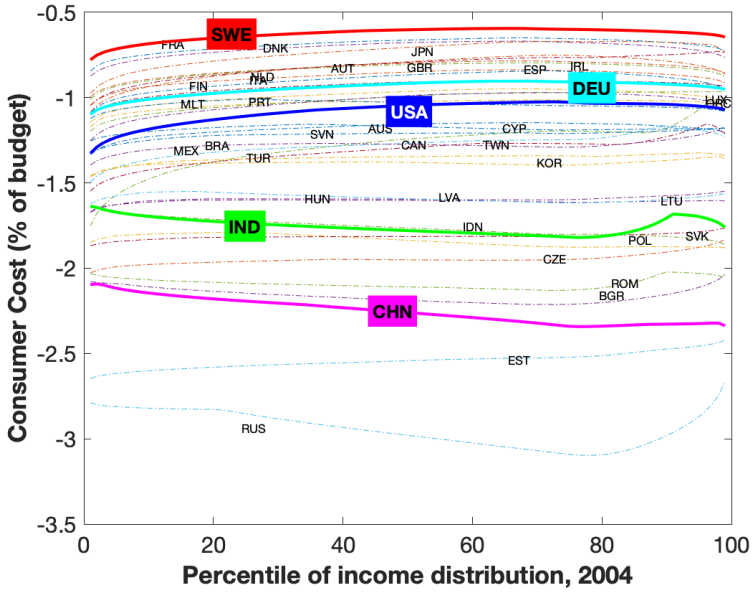
Notes: This figure shows the global distribution of the consumer cost under a global uniform carbon price of 30 USD per ton of CO_2 simulated in 2004 (40 WIOD countries). The horizontal axis shows percentiles of the income/expenditure distribution across the 4.2 billion inhabitants of the 40 WIOD countries in 2004. The consumer cost is the welfare loss (negative values) equivalent to losing a share of the total expenditure budget (dashed) and approximated with a 10th degree polynomial (solid). Shaded regions are 95% confidence intervals from 500 separate simulations, each using a different set of parameters drawn from the joint normal distributions from estimations (15), (16) and (20).

regressive—with larger relative costs to low-income consumers—and vice versa. In rich nations—such as Germany, Sweden and the United States—carbon pricing looks regressive. In developing nations—such as China and Indonesia—it looks somewhat progressive. This is in line with single-country studies, which find weak to moderate regressivity in rich (Poterba, 1991; Grainger and Kolstad, 2010) and progressivity in poor ones (Datta, 2010; Sterner, 2012; Dorband et al., 2019).

Figure 3 also suggests a third, more nuanced insight: The consumer incidence of carbon pricing varies much more strongly between than within countries. Simply put, the slope of individual lines in Figure 3 is much less important than the distances between them. For example, the average consumer cost in China is roughly

twice as large as that in the United States. While there is a mild difference in cost between American consumers at the 10th percentile of the income distribution (equal to 1.2% of expenditures) and those at the 90th percentile (1.0%), the difference is much more pronounced in comparison to Chinese consumers at the 10th (2.1%) and 90th (2.2%) percentiles respectively. These differences are driven both by a more emissions-intensive mix of consumption (Caron and Fally, 2018) and more emissions-intensive value chains in production (Copeland and Taylor, 1994; Levinson, 2009). It has long been recognized that national economic structure has important repercussions for environmental policy (Whalley and Wigle, 1991; Shah and Larsen, 1992). My analysis suggests that differences between countries are more important for the global cost of carbon pricing than those within countries.

Figure 3: Global price of 30 USD/t - Within-country consumer cost



Notes: This figure shows the distribution of the consumer cost in each country under a global uniform carbon price of 30 USD per ton of CO_2 simulated in 2004 (40 WIOD countries). The horizontal axis shows percentiles of the income/expenditure distribution within each of the 40 WIOD countries in 2004. The consumer cost is the welfare loss (negative values) equivalent to losing a share of the total expenditure budget.

Adding country-specific "Carbon Dividends":

We have so far focused on the cost to consumers from higher prices. But carbon pricing may also generate substantial revenues, which governments can use to partially offset the costs. Figure 4a shows how revenue recycling may change the global consumer cost of carbon pricing. Specifically, I assume that governments redistribute 100% of the revenue generated in each country, splitting it equally among domestic consumers. Such carbon dividends feature in many carbon pricing proposals, including that by the Climate Leadership Council for the United States.

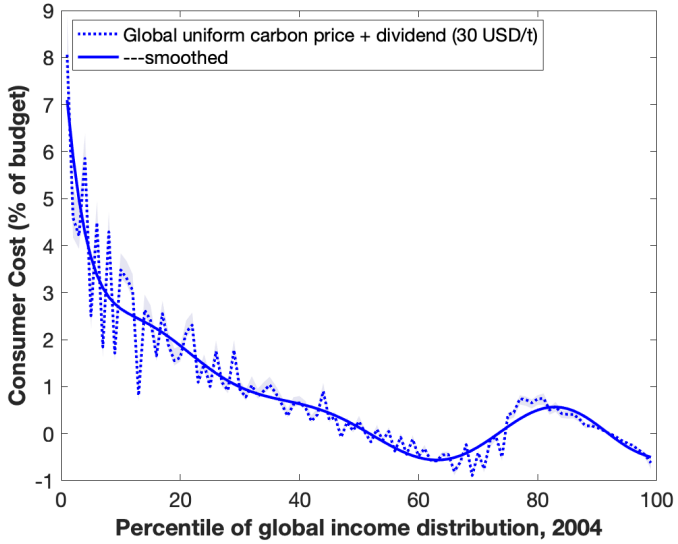
Figure 4a shows that the global consumer cost of a global 30USD/t carbon price paired with carbon dividends is strongly progressive. While higher prices disproportionately affect lower income consumers as share of their budget (Figure 2), the equal lump sum payment more then compensates them[15]. This is so, because higher income consumers contribute more to the carbon pricing revenue in absolute terms, as can be seen in Appendix Figure 10. Overall, 70% of all consumers worldwide are better off after carbon dividends are paid out.

Figure 4b shows that the same progressive net effect after lump sum redistribution holds within most countries. Further, it appears that the progressive nature of carbon dividends is more pronounced in more unequal countries, where the difference between the average consumer (who pays for the carbon dividend) and low-income consumers is bigger. For example, Chinese consumers at the 10th income percentile now experience a larger net benefit than American consumers at the 10th percentile (4.7% compared to 2.6%). While the mean consumer cost is negative in all countries even after the carbon dividend, the median consumer is now better off in 21 out of the 40 WIOD countries. These results suggest two insights. First, national carbon dividends make the consumer cost of carbon pricing progressive—both globally and within countries. Second, in a large number of countries a majority of consumers is better off than before, even without considering mitigation benefits. Importantly, these results are based on revenue recycling by national governments and do not require any transfers between countries.

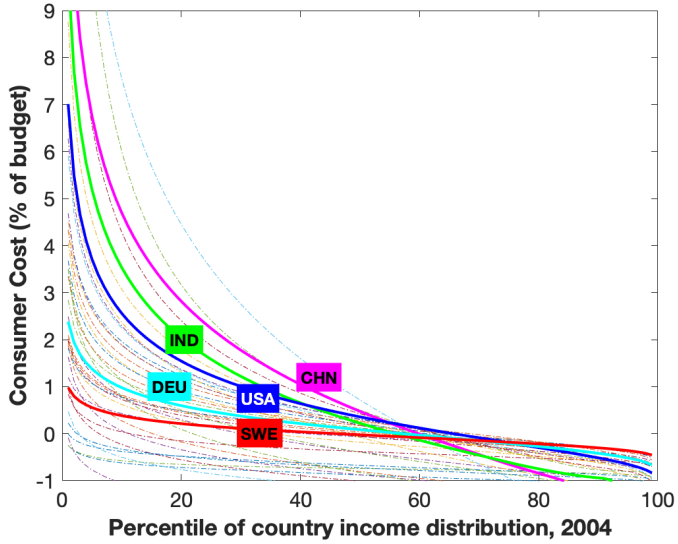
[15]When considering revenue use, it does matter where the pricing occurs. Figure 4a assumes that the revenue is collected and redistributed in the country where emissions occur—pricing emissions at the source. Appendix Figure 11 shows that the same pattern holds under a consumption tax.

Figure 4: Global price of 30 USD/t and national carbon dividend - Consumer cost

(a) Global distribution



(b) Within-country distribution



Notes: Consumer cost under a global uniform carbon price of 30 USD per ton of CO_2 simulated in 2004 (40 WIOD countries), net of the benefits from a per capita carbon dividend in each country. The horizontal axis shows percentiles of the income/expenditure distribution, both globally (Panel a) and within each of the 40 WIOD countries (Panel b) in 2004. Otherwise equivalent to Figure 2 (Panel a) and Figure 3 (Panel b).

4.2. Scenario 2: The EU Emissions Trading Scheme (ETS)

The European Union (EU) introduced the EU Emissions Trading Scheme (ETS) in 2005. It was the first coordinated carbon pricing mechanism by a group of developed countries. While much research has been devoted to the effectiveness of the EU ETS, less attention has been paid to how its costs may be distributed across EU consumers. Here, I estimate the consumer cost of a stylized EU ETS across consumers in participating countries. Of the 28 current EU member states, my sample includes 27 (all except Croatia which joined in 2013)[16]. I calibrate my model to 2004, the year before introduction, and estimate the consumer cost of introducing the ETS in these 27 countries. The price in the EU ETS fluctuated mostly around 20-25 EUR/t throughout 2005[17]. I simulate a carbon price of 30 USD/t in the 27 EU member countries levied on all emissions in the sectors targeted by the ETS at launch[18].

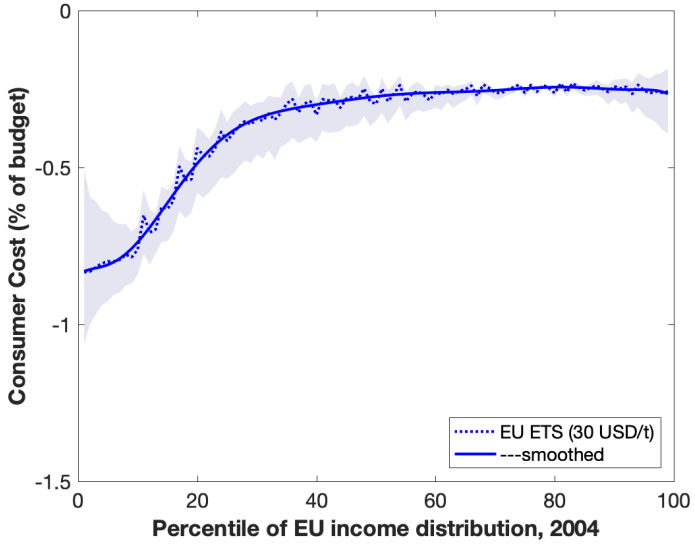
[16] Among the 28 EU member states in 2018, Bulgaria and Romania joined in 2007. Croatia joined in 2013. Bulgaria and Romania are included here as participants of the EU ETS. In addition to the 28 EU member states, the EU ETS also operates in Iceland, Liechtenstein and Norway, which are not in the sample.

[17] The first phase of the EU ETS, running from 2005 to 2007, was considered a learning phase. Almost all allowances were initially distributed free of charge based on estimates. Due to oversupply, the allowance price collapsed in 2007.

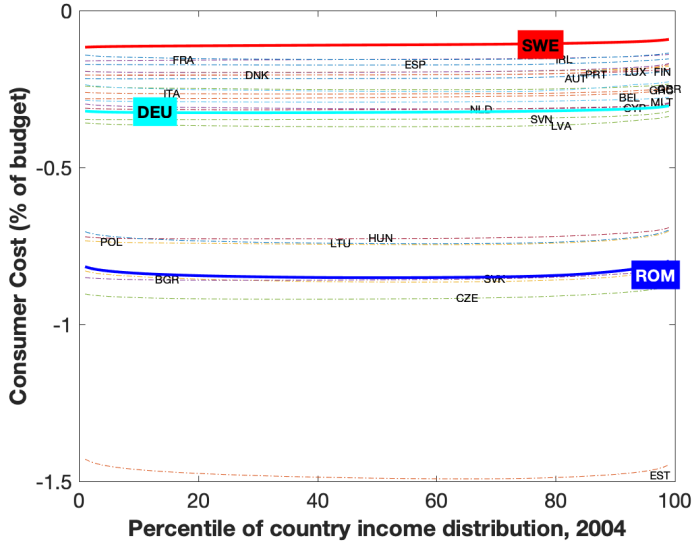
[18] The EU ETS covered about half of total CO_2 emissions, mostly in power generation and energy-intensive industries. To emulate the intended sector targeting of the first phase of the EU ETS, I apply the carbon price to emissions in the following WIOD sectors: "Electricity, Gas and Water Supply", "Mining and Quarrying", "Pulp, Paper, Printing and Processing", "Coke, Refined Petroleum and Nuclear Fuel", "Chemicals and Chemical Products", "Other Non-Metallic Mineral", and "Basic Metals and Fabricated Metal". While these sectors may not be fully congruent with the actual targeting of the EU ETS, which e.g. discriminated by plant size within industry, it should come close. Notably, the distribution of costs presented here is qualitatively similar, albeit smaller, than the costs under a scenario where the EU carbon price applies to all sectors.

Figure 5: EU price of 30 USD/t - Consumer cost

(a) EU-wide distribution



(b) Within-country distribution



Notes: This figure shows the distribution of the consumer cost under an EU-wide (27 countries) uniform carbon price of 30 USD per ton of CO_2, applied to the EU ETS target sectors and simulated in 2004 (model includes 40 WIOD countries). The horizontal axis shows percentiles of the income/expenditure distribution, both EU-wide (Panel a) and within each of the 27 EU countries among the 40 WIOD countries (Panel b) in 2004. Otherwise equivalent to Figure 2 (Panel a) and Figure 3 (Panel b).

Figure 5a shows how the estimated consumer cost due to higher prices is distributed across the circa 490 million EU residents. The overall consumer cost of an EU-wide carbon price of 30 USD/t appears more regressive. Consumers in the bottom 10 % of the EU income distribution incur a cost equivalent to around 0.8% of their total expenditure. The cost to consumers in the top half of the income distribution is less than 0.3%. Again, this is largely driven by differences between countries rather than within.

Figure 5b shows the distribution of consumer cost in the 27 EU member states. Just like for the global carbon price, we see only modest variation in the distributional incidence within countries, but larger differences between EU member states. Carbon pricing imposes a much larger cost on the average consumer in the EU member states with lower incomes. The cost is particularly large for consumers in the Eastern European and Baltic states. Simply put, consumers in Romania experience a much higher cost than consumers in Germany or Sweden, no matter if they have high or low incomes. Again, this regressive incidence of an EU carbon price is due to a dirtier consumption mix of lower-income consumers as well as higher emissions intensities of industries—and in particular power generation—in lower-income EU countries. Estonia is a case in point, where the high penetration of shale oil results in particularly large consumer costs from carbon pricing. The median EU consumer incurs a welfare loss of ca. 60-70 USD from an EU-wide carbon price of 30 USD/t in 2004 (Appendix Figure 13).

It is important to note that my analysis is an *ex ante* evaluation of the EU ETS as it may have been intended. I do not evaluate the EU ETS as it was realized. There are a number of reasons why the realized outcome of the EU ETS may have differed from my simulation. The EU ETS, and in particular the first phase, has been fraught by a range of implementation and design issues. A large literature documents these and evaluates the effects that the EU ETS had (surveyed for example in Ellerman et al., 2016; Martin et al., 2016). But my results suggest one characteristic of the EU ETS which has received less attention—the potentially regressive effects of carbon pricing across EU citizens, which could disproportionately affect consumers in Eastern European and Baltic member states.

4.3. Scenario 3: A Border Carbon Adjustment (BCA) in the EU

In a final scenario, I estimate the consumer cost from pricing the emissions content of traded goods. An important concern about carbon pricing is that it may weaken the competitiveness of domestic industries relative to foreign industries subject to less stringent policy. One result could be carbon leakage—emissions simply move abroad instead of being avoided altogether (Levinson and Tayler, 2008; Aichele and Felbermayr, 2015; Fowlie et al., 2016). Because this competitiveness channel receives significant public attention, governments can be concerned both about the actual damage to industrial competitiveness as well as potential resistance to carbon pricing from a perceived threat.

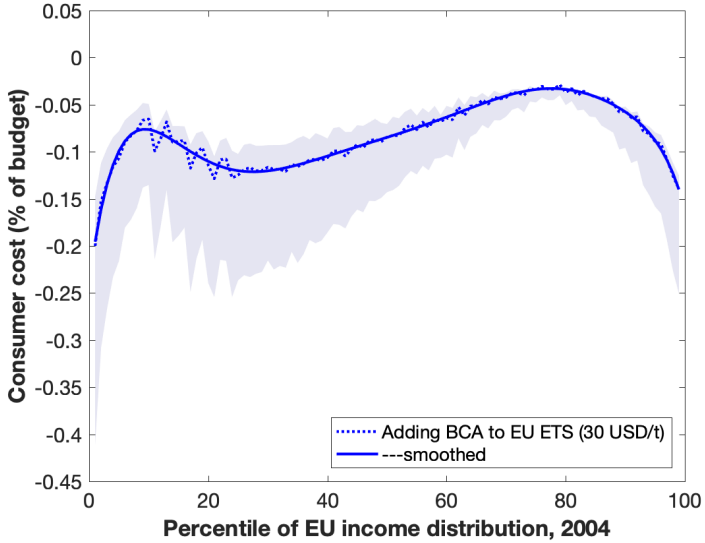
Border Carbon Adjustments (BCA) could help reduce the competitive pressure from carbon pricing. They feature adjustments of prices at the border, extending the coverage of a carbon price to goods from countries with less stringent carbon pricing regimes (Felder and Rutherford, 1993). BCA are most commonly proposed in the form of carbon tariffs on the embodied carbon of imported goods. In theory, BCA are an elegant solution to the problem of carbon leakage (Markusen, 1975; Hoel, 1996). In practice, their potential for leakage reduction is debated and so is their legal status under the rules of free trade. They too may increase consumer prices, this time, however, for imported goods. Despite their theoretical appeal, there is to date scarce evidence on the distributional effects of BCA. My framework combines distributional welfare analysis with differentiated goods trade and global value chains. It is thus uniquely suited to investigate the consumer cost of BCA. To do so, I consider a scenario, in which a carbon price of 30 USD/t in the EU is extended to traded goods[19].

Figure 6a shows how the additional cost of such a BCA is distributed. It represents the cost difference between two scenarios—an EU-wide carbon price of 30 USD/t with and without BCA. Across the 490 million residents of the EU, I estimate that welfare losses follow an inverse U-shape.

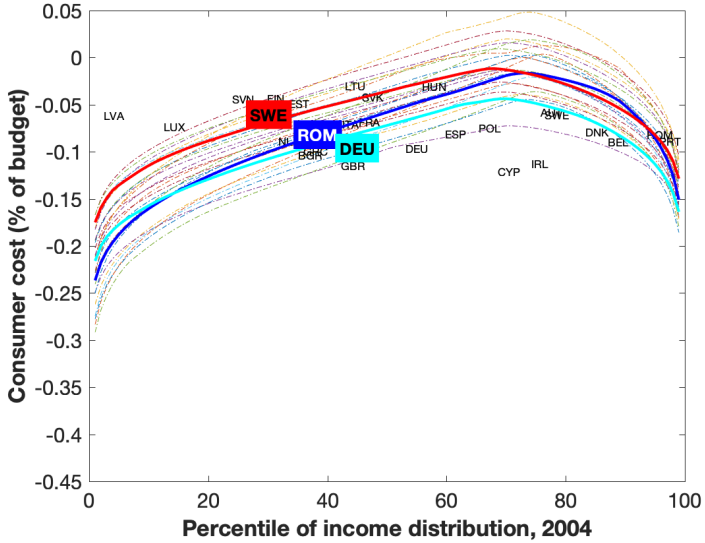
[19] In the analysis of the EU ETS, I limited carbon pricing to emissions in energy-intensive sectors that were initially targeted by the EU ETS. Here I consider BCA to complement a domestic carbon price covering all sectors. The results are qualitatively similar—albeit with smaller costs—for a BCA to complement the an EU-wide carbon price only in the energy-intensive sectors initially targeted by the EU ETS.

Figure 6: EU Border Carbon Adjustment of 30 USD/t - Consumer cost

(a) EU-wide distribution



(b) Within-country distribution



Notes: Consumer cost under a Border Carbon Adjustment to complement an EU-wide (27 countries) uniform carbon price of 30 USD per ton of CO_2, applied to all sectors and simulated in 2004 (model includes 40 WIOD countries). The horizontal axis shows percentiles of the income/expenditure distribution, both EU-wide (Panel a) and within each of the 27 EU countries among the 40 WIOD countries (Panel b) in 2004. Otherwise equivalent to Figure 2 (Panel a) and Figure 3 (Panel b).

Overall, the consumer cost from BCA is estimated to be rather small, with the largest cost, to consumers in the bottom percentile of the income distribution, equivalent to 0.2% of annual expenditure. Figure 6b shows the distribution of the consumer cost within countries. It follows an inverted U-shape—consumers with the highest and lowest incomes are incur the largest cost. This pattern might be due to both groups consuming larger shares of imported goods which experience a price increase due to BCA. At the bottom of the income distribution this is driven by imported necessities (e.g. textiles from India), while at the top it is driven by imports with relatively higher income elasticities (e.g. textiles from the United States). Contrary to the other two scenarios, the cost of BCA varies more strongly within countries than between them. Differences between countries are rather small—with perhaps Cyprus as the notable exception—and there is no clear relationship with national income levels. This may be due to a relatively similar composition of aggregate imports into the different EU countries. The cost of such a BCA to the median EU consumer is about 20 USD in 2004 (Appendix Figure 15).

Leakage reduction: This article contributes to the literature on BCA by estimating how its consumer cost may be distributed. It also validates previous findings on the potential of BCA for leakage reduction. In the 40 countries covered, total CO_2 emissions in 2004 were 20.4Gt. I estimate that an EU-wide carbon price of 30 USD/t applied to all sectors would have led to a global emissions reduction of 2.2Gt. Complementing the EU-wide price with a BCA would have increased the reduction by about 25% to 2.8Gt. This is in line with the previous literature, which finds significant leakage reduction potential for BCA[20]. The rough estimate of 600 million tons less in CO_2 emissions at a cost of 20 USD for the median EU consumer suggests that the BCA would have led to a net welfare gain for EU consumers, even before considering tariff revenues and gains for domestic industries.

[20]Studies using rich CGE models find that BCA have the potential to significantly reduce leakage (e.g. Elliott et al., 2010; Böhringer et al., 2016a,b) and shift the burden of emission reduction to countries without domestic carbon prices (Aldy and Pizer, 2015; Böhringer et al., 2018). Using trade gravity approaches, Aichele and Felbermayr (2015) predict significant leakage in absence of BCA and Larch and Wanner (2017) estimate that carbon tariffs somewhat reduce leakage while imposing a net welfare loss on representative consumers in developing countries.

5. Robustness

The results presented above rely on a number of model assumptions outlined in Section 2 as well as the parameter estimates obtained in Section 3. Below I show results from robustness checks which support my confidence in the results.

5.1. Consistency with consumption micro-data (CEX)

My approach follows Fajgelbaum and Khandelwal (2016) in identifying global demand system parameters from aggregate trade flows. The distribution of consumption within countries is extrapolated based on income elasticities estimated from aggregate expenditure differences between countries[21]. Simply put, because richer countries buy more textiles from the United States and fewer textiles from India, I expect richer consumers within countries to buy more textiles from the United States and fewer textiles from India. This is of course a rather strong assumption.

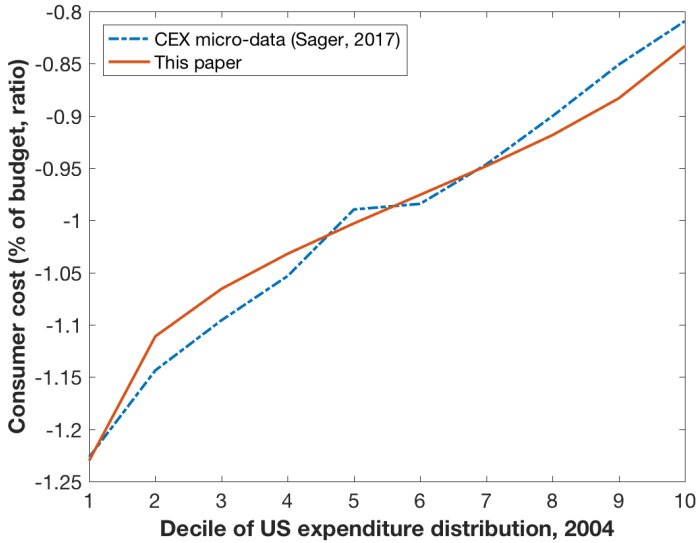
To test this assumption, I compare my model to micro-data from the United States. I focus on the initial incidence of carbon pricing, the cost to consumers of introducing a carbon price of 1 USD/t. Figure 7a compares cost estimates across the US income distribution in 2004. The red (solid) line shows estimates from my structural demand model. The blue (dashed) line shows estimates based on household expenditure data from the US Consumer Expenditure Survey (CEX). The CEX reports consumer expenditures on over 600 categories, which I map into the 35 WIOD sectors[22]. Both are normalized to 1 on average. The two different approaches yield very similar estimates of the relative distribution of consumer cost from carbon pricing within the United States. This is reassuring. Still, I cannot deny the possibility that the demand system I estimate might be a better fit for some countries than others. In any case, given the dominance of between-country differences, which are based on WIOD data, any potential bias in within-country estimates is unlikely to significantly alter results in Figure 2.

[21] Such extrapolation could be avoided by using harmonized micro-data from all countries which describes consumption patterns at different income levels, including shares of goods by origin. I am not aware of such data.

[22] Data and methods are outlined in Sager (2019). Both measures are normalized to 1.

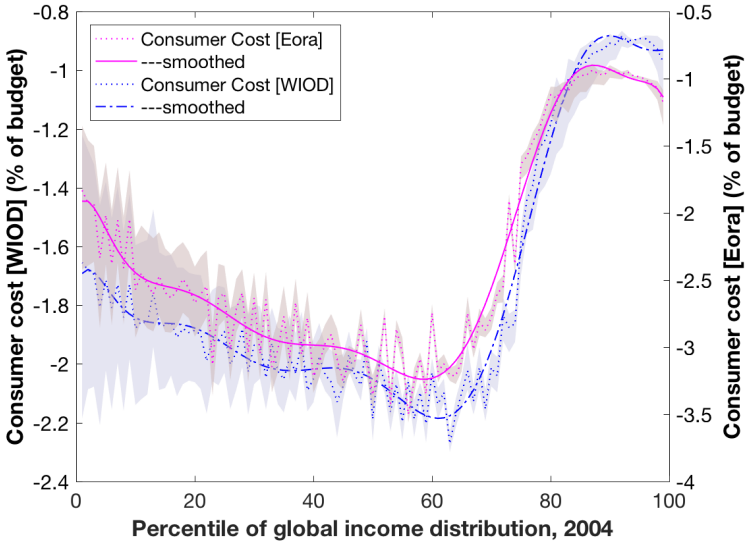
Figure 7: Robustness of main results to alternative data sources

(a) Comparison to US consumption micro-data (CEX)



Notes: Comparison of initial incidence of carbon pricing between demand system (this article) and empirical estimates based on household consumption data from the Consumer Expenditure Survey (matched to emissions in Sager, 2019). The horizontal axis shows income deciles of the US expenditure distribution. The vertical axis shows the relative exposure of consumers in each decile to the first marginal USD of carbon pricing in 2004, as a ratio to the average.

(b) Comparison to alternative input-output data (Eora)



Notes: Comparison of simulation results using WIOD data (used throughout this article) and Eora data. Both show the simulated consumer cost under a global uniform carbon price of 30 USD per ton of CO_2 simulated in 2004. WIOD results [left axis] are the same as shown in Figure 2. Eora results [right axis] are based on newly estimated model parameters and new input-output data, with a carbon price applied to all 189 Eora countries and greenhouse gases (Kyoto classification) emitted from a large range of activities (including land use). Both shown for the subset of 40 countries in WIOD.

5.2. Alternative input-output data (Eora)

The above results are based on parameter values estimated using data from the World Input-Output Database (WIOD). While WIOD is one of the most commonly used sources for multi-region input-output (MRIO) data, it is subject to a number of limitations. WIOD covers a significant portion of the world economy—including the entirety of the EU as well as the United States, China, India and a number of other countries—but far from all of it. Specifically, WIOD provides harmonised data on 35 sectors in 40 countries. As a consequence, Figure 2 is limited to circa 4.2 out of the over 7 billion people worldwide. To check for the robustness of my results, I re-estimate the above incidence based on an alternative MRIO data source—the Eora MRIO database. I use the symmetric and harmonised version of Eora (Eora 26), which covers 189 countries and 26 sectors. The most recent year available is 2015.

Figure 7b compares model estimates using Eora data to those obtained using WIOD. The left panel is equivalent to Figure 2—the incidence of a global carbon price of 30 USD/t in 2004 across the 40 WIOD countries. The right panel shows the same result using Eora data. The Eora results are also limited to the 4.2 billion inhabitants of the 40 WIOD countries (results for all 189 countries can be found in Appendix H). Eora also provides an alternative account of greenhouse gas emissions. I choose emissions accounts, which include six greenhouse gases[23] emitted from a large range of activities (including land use). The two panels are based on entirely separate estimates of consumer and producer elasticities, industry emissions intensities, and trade flows. Reassuringly, the resulting incidence patterns are highly similar.

[23] Specifically, the data includes six Kyoto gases and gas groups as reported in the PRIMAP-hist database: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), hydrofluorocarbons(HFCs), and perfluorocarbons (PFCs). Results look qualitatively similar if the analysis is restricted to CO_2 emissions from fossil-fuel combustion as reported by the IEA.

6. Conclusion

Using a structural model of the global economy, parameterized using bilateral trade data, I have estimated the global consumer incidence of three carbon pricing scenarios. I have found that a global uniform carbon price is globally regressive, and that this regressivity is almost entirely due to differences between countries than within. This is an important finding in light of the strong focus on within-country incidence in the literature to date. Interestingly, allowing for country-level carbon dividends, which redistribute carbon pricing revenue equally among consumers, renders such a policy strongly progressive both globally and within most countries. No transfers between countries are needed for this result.

Similarly, I have found that the consumer cost of the EU ETS introduced in 2005 may have been regressive. Again, this is driven by differences between countries, with a particularly high cost to consumers in Eastern European and Baltic member states. Finally, I have shown that the consumer cost of a hypothetical BCA to complement an EU-wide carbon price, would have followed an inverted U-shape—with the highest cost to consumers at either end of the EU income distribution.

These estimates have focused on the cost to consumers due to higher final goods prices. A complete welfare analysis of climate policy would require contrasting this consumer cost with the other costs and benefits of climate policy (Fullerton, 2011). First, the net costs of carbon pricing should be contrasted with the benefits of reduced climate damage (see Dietz et al., 2018, for a recent survey). Models that disaggregate the social cost of carbon (SCC)—the benefit of reducing CO_2 emissions by one unit today—find significant differences between regions. In sum, the evidence suggests that climate mitigation is likely to disproportionately benefit countries that are simultaneously hot and poor (Dell et al., 2012; Burke et al., 2015; Ricke et al., 2018). This implies that mitigation benefits may weaken or even reverse any potential regressivity in the consumer cost of carbon pricing. I leave a systematic analysis of the net incidence for future work. Second, the within-country literature suggests a potential for progressive "source-side" effects—the shift in industry composition and returns to factor inputs—resulting from climate policy (Goulder et al., 2019). Further research may be necessary to determine the

global "source-side" incidence of carbon pricing.

Finally, my results support the notion that the distributional effect of carbon pricing will ultimately depend on the use of revenues. This is in line with the within-country literature, which finds that energy taxes become less regressive, and may even become progressive, when the revenue is used for lump-sum per capita rebates (Rausch et al., 2011; Williams et al., 2015) or other progressive measures such as food subsidies Gonzalez (2012). This is exactly what I find, with the important additional insight that no between-country transfers are required to make the consumer cost of carbon pricing progressive both globally and within countries.

In conclusion, this article is the first to estimate how the consumer cost of carbon pricing is distributed globally—both between and within many countries. As any large-scale welfare analysis, my results rely on a number of assumptions and empirical estimates. I have shown that my findings replicate with an alternative data source and match well estimates using more detailed micro-data. The results have potentially important implications for the equitable design of global climate policy.

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For Online Publication

The Global Consumer Incidence of Carbon Pricing: Evidence from Trade

APPENDIX

by Lutz Sager

A. Derivation of Proposition 1

We consider the change in the log of indirect utility of consumer h due to infinitesimal changes in log prices $\{p_j\}_{j=1}^{J}$ and the log of expenditure $\hat{x}_h$. Fajgelbaum and Khandelwal (2016) show that the change in indirect utility is:

$$\hat{v}_h = \sum_{j=1}^{J} \frac{\partial \log v(x_h, \mathbf{p})}{\partial \log p_j} \hat{p}_j + \frac{\partial \log v(x_h, \mathbf{p})}{\partial \log x_h} \hat{x}_h \tag{21}$$

Equivalent variation is then defined as the change in log expenditures, $\hat{\omega}_h$ that would lead to the indirect utility change $\hat{v}_h$ at constant prices:

$$\hat{v}_h = \frac{\partial \log v(x_h, \mathbf{p})}{\partial \log x_h} \hat{\omega}_h \tag{22}$$

After applying Roy's identity $\left(y_{h,j} = -\frac{\partial v(.)/\partial p_j}{\partial v(.)/\partial x_h}\right)$, the individual welfare effect can be separated into three elements:

$$\begin{aligned} \hat{\omega}_h &= \sum_{j=1}^{J} \left(-\hat{p}_j\right) s_{j,h} + \hat{x}_h \\ &= \sum_{j=1}^{J} \left(-\hat{p}_j\right) S_j + \sum_{j=1}^{J} \left(-\hat{p}_j\right) \left(s_{j,h} - S_j\right) + \hat{x}_h \\ &= \hat{W} + \hat{\psi}_h + \hat{x}_h \end{aligned} \tag{23}$$

Here, $\hat{x}_h$ is the income effect, $\hat{W}$ is the aggregate expenditure effect and $\hat{\psi}_h$ is the individual expenditure effect of consumer h. $\hat{\psi}_h$ captures that consumers with different income levels may be differentially affected by price changes because they have a different expenditure composition.

Using the expenditure shares under the AIDS demand structure, we can use the fact that $s_{j,h} - S_j = \beta_j \log\left(\frac{x_h}{\tilde{x}}\right)$, to re-write the individual expenditure effect:

$$\hat{\psi}_h = -\left(\sum_{j=1}^{J} \beta_j \hat{p}_j\right) \log\left(\frac{x_h}{\tilde{x}}\right) \tag{24}$$

This finally gives the welfare change of consumer h as:

$$\hat{\omega}_h = \hat{W} - \left(\sum_{j=1}^{J} \beta_j \hat{p}_j\right) \log\left(\frac{x_h}{\tilde{x}}\right) + \hat{x}_h \tag{25}$$

B. Derivation of Proposition 3

Given the assumed initial price changes to $p_j^{new} = (1+\tau\varepsilon_j)p_j$, the new share of inputs j in the expenditure of sector k relative to the old share would become:

$$\frac{S_{jk}^{new}}{S_{jk}} = (1+\tau\varepsilon_j)^{(1-\sigma_k)} \left(\frac{P_k^{new}}{P_k}\right)^{(\sigma_k-1)} \tag{26}$$

Assuming unchanged value-added shares κ_k, we get an updated 'Direct Requirement Matrix' $\mathbf{C}^{new}$ which has elements:

$$c_{jk}^{new} = \frac{S_{jk}^{new}}{S_{jk}} \frac{P_k^{new}}{1+\tau\varepsilon_j} = \left(\frac{P_k^{new}}{1+\tau\varepsilon_j}\right)^{\sigma_k} c_{jk} \tag{27}$$

This "Direct Requirement Matrix" at new prices now has a slightly different interpretation than the one at original prices. The original "Direct Requirement Matrix" had elements c_{jk} which characterised the dollar value of input required from sector j to produce one dollar value of final output in sector k.

Let us now define a new unit of measurement for each sector k, which we shall call "previous dollar value unit" (PDU). One PDU is equal to the amount of good k that could be bought at the original prices (we assume throughout that prices of good k used as intermediate inputs are the same as when k is bought as final good). The elements of the new "Direct Requirement Matrix" is then interpreted as follows: After the price change, to generate one PDU of output in sector k we require c_{jk}^{new} units (in PDU) of intermediate good j. Essentially, I normalise all initial prices to $p_j = 1\ \forall j$. This works because only relative price changes matter.

The "direct emissions intensity" $\delta_j^{new} = \delta_j$ remains unchanged in this step but now also characterises the direct emissions per PDU output (i.e. the emissions related to the value-added for one unit produced). But of course, the adjustments to input use will themselves change the structure of supply chains and, in consequence, the emissions intensities ε_k. Calculating new "total emissions intensities" per PDU should then be $\mathbf{e}^{new} = (I - \mathbf{C}^{new})^{-1}\mathbf{d}$ and the final goods price of j including the carbon price is $1+\tau\varepsilon_j^{new}$. I approximate this new structure numerically as described in Appendix C.

C. Numerical approximation of new equilibrium production

I approximate numerically the new equilibrium supply chain structure $\mathbf{C}^{new}$, emission intensities ε_j^{new} and prices $p_{jk}^{new} = (1 + \tau_{jk}\varepsilon_j^{new})p_{jk}$. I do this using an iterative process with the following steps:

1. Calculate initial adjustment of input requirements $\{c_{jk}^{new}\}$ when carbon price is levied on emissions intensities $\{\varepsilon_j\}$ based on original production $\{c_{jk}\}$
2. Calculate emissions intensities $\{\varepsilon_j^{new}\}$ based on adjusted production $\{c_{jk}^{new}\}$
3. Use new $\{\varepsilon_j^{new}\}$ to calculate further adjustment in production $\{c_{jk}^{new_2}\}$
4. Re-calculate $\{\varepsilon_j^{new_2}\}$ based on adjusted production $\{c_{jk}^{new_2}\}$
5. Back to step 1.

In all simulations, the procedure converges very quickly to a state where additional rounds of adjustment are negligible.

D. Parameter Robustness

Table 2: Average estimates of income semi-elasticity by country

Country	$\overline{\hat{\beta}}$	**Country**	$\overline{\hat{\beta}}$
AUS	0.017	IRL	0.000
AUT	0.002	ITA	0.009
BEL	-0.019	JPN	0.039
BGR	-0.006	KOR	0.007
BRA	-0.016	LTU	0.000
CAN	-0.007	LUX	-0.011
CHN	-0.005	LVA	0.000
CYP	0.013	MEX	-0.019
CZE	-0.006	MLT	0.004
DEU	-0.003	NLD	-0.007
DNK	0.002	POL	-0.003
ESP	0.003	PRT	-0.004
EST	0.001	ROM	-0.004
FIN	0.008	RUS	-0.005
FRA	-0.004	SVK	-0.003
GBR	0.014	SVN	-0.002
GRC	0.013	SWE	0.002
HUN	0.001	TUR	-0.001
IDN	-0.026	TWN	0.016
IND	-0.031	USA	0.097

Notes: Average estimates of the income (semi)-elasticities as estimated from (15) and (16) for the WIOD cross-section 2004. Country averages across the 35 supply sectors each.

Table 3: Average estimates of income and price elasticities by sector

	WIOD Sector	$\overline{\hat{\beta}}$	$\overline{\hat{\gamma}}$
1	Agriculture, Hunting, Forestry and Fishing	-0.022	0.007
2	Mining and Quarrying	0.000	0.001
3	Food, Beverages and Tobacco	-0.016	0.015
4	Textiles and Textile Products	-0.004	0.002
5	Leather, Leather and Footwear	-0.001	0.001
6	Wood and Products of Wood and Cork	0.000	0.000
7	Pulp, Paper, Paper , Printing and Publishing	0.002	0.002
8	Coke, Refined Petroleum and Nuclear Fuel	0.000	0.003
9	Chemicals and Chemical Products	-0.001	0.003
10	Rubber and Plastics	0.000	0.001
11	Other Non-Metallic Mineral	0.000	0.001
12	Basic Metals and Fabricated Metal	0.000	0.002
13	Machinery, Nec	-0.005	0.005
14	Electrical and Optical Equipment	-0.004	0.005
15	Transport Equipment	-0.003	0.006
16	Manufacturing, Nec; Recycling	0.001	0.002
17	Electricity, Gas and Water Supply	0.000	0.006
18	Construction	-0.014	0.041
19	Sale, Mntnce and Repair Motor Veh.; Retail Sale of Fuel	0.003	0.004
20	Wholesale Trade and Commission Trade, Except of Motor Veh.	0.001	0.015
21	Retail Trade, Except of Motor Veh.; Repair of Household Goods	0.001	0.017
22	Hotels and Restaurants	0.006	0.014
23	Inland Transport	-0.008	0.006
24	Water Transport	-0.001	0.000
25	Air Transport	0.000	0.001
26	Other Supporting and Aux. Transport Activities; Travel Agencies	0.002	0.002
27	Post and Telecommunications	0.000	0.006
28	Financial Intermediation	0.006	0.013
29	Real Estate Activities	0.015	0.031
30	Renting of M&Eq and Other Business Activities	0.003	0.008
31	Public Admin and Defence; Compulsory Social Security	0.007	0.040
32	Education	0.004	0.015
33	Health and Social Work	0.022	0.026
34	Other Community, Social and Personal Services	0.004	0.016
35	Private Households with Employed Persons	0.001	0.001

Notes: Average estimates of the income (semi)-elasticities and price elasticities as estimated from (15) and (16) for the WIOD cross-section 2004. Sector averages across the 40 origin countries each.

Table 4: Consistency of parameter estimates - $\hat{\beta}$

	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
2000	1.00	0.97	0.98	0.96	0.92	0.89	0.82	0.69	0.58	0.66
2001	0.97	1.00	0.96	0.94	0.92	0.88	0.81	0.69	0.58	0.64
2002	0.98	0.96	1.00	0.99	0.96	0.93	0.88	0.77	0.67	0.73
2003	0.96	0.94	0.99	1.00	0.99	0.97	0.93	0.84	0.75	0.80
2004	0.92	0.92	0.96	0.99	1.00	0.99	0.97	0.90	0.82	0.85
2005	0.89	0.88	0.93	0.97	0.99	1.00	0.99	0.93	0.86	0.89
2006	0.82	0.81	0.88	0.93	0.97	0.99	1.00	0.97	0.92	0.93
2007	0.69	0.69	0.77	0.84	0.90	0.93	0.97	1.00	0.98	0.97
2008	0.58	0.58	0.67	0.75	0.82	0.86	0.92	0.98	1.00	0.97
2009	0.66	0.64	0.73	0.80	0.85	0.89	0.93	0.97	0.97	1.00

Notes: Pairwise correlation, 1400 income elasticities estimated from (15) and (16), WIOD cross-sections.

Table 5: Consistency of parameter estimates - $\hat{\gamma}$

	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
2000	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99
2001	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99
2002	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	1.00
2003	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2004	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2005	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2006	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2007	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2008	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2009	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Notes: Pairwise correlations, 35 price elasticity parameters estimated from (15), WIOD cross-sections.

Table 6: Consistency of parameter estimates - $\hat{\sigma}$

	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
2000	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.98
2001	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.98
2002	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.98
2003	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99
2004	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99
2005	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2006	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	0.99
2007	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00
2008	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00
2009	0.98	0.98	0.98	0.99	0.99	1.00	0.99	1.00	1.00	1.00

Notes: Pairwise correlations, 35 CES elasticities estimated from (20), WIOD cross-sections.

E. Comparison to alternative modeling approaches

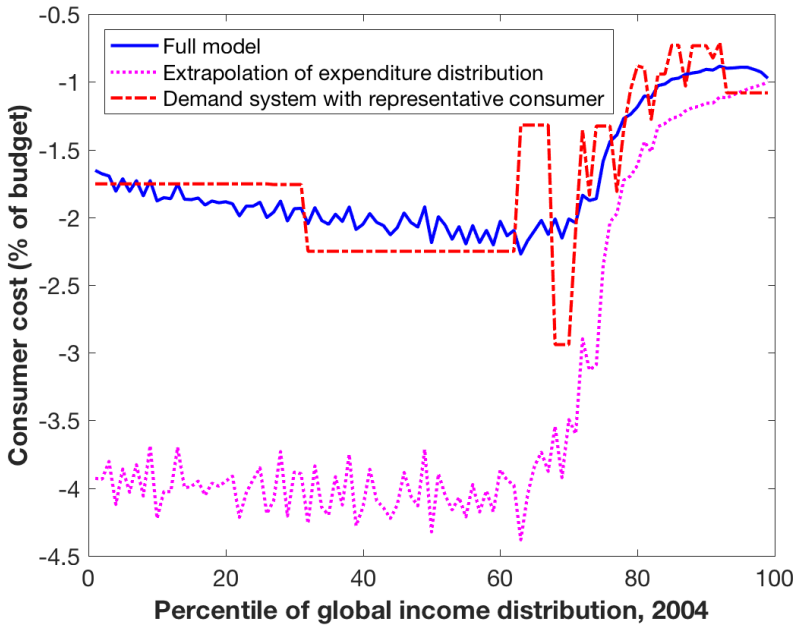
The results presented in this paper are based on a model of the global economy which incorporates adjustment margins both on the supply and the demand side. Figure 8 compares estimates. Much of the literature estimating the within-country incidence of energy taxes uses consumer expenditure micro-data (Grainger and Kolstad, 2010; Williams et al., 2015, e.g.). Often, a first approximation of the incidence can be based on the emissions-intensity of observed consumption. We have seen above that my global model produces similar results for the initial incidence of carbon pricing, at least for the United States. However, at higher prices we may expect divergence as my model allows consumers to shift away from emissions-intensive goods. Figure 8 compares estimates from my full model to such a simplified approach, ignoring both demand adjustments by consumers and input substitution by producers (dotted line). This would result in substantial over-estimation of the global consumer cost and its regressivity[24].

Meanwhile, an approach ignoring the within-country heterogeneity of consumers—assuming one representative consumer per county (dashed line)—produces estimates that are similar to the full model. This is in line with the above finding that the global incidence of carbon pricing is largely driven by between-country differences. To see this more clearly, we make use of Equation (6) to separate the variation in global consumer cost into two parts—the variation of average consumer cost between countries and the variation within countries around those averages. For the global uniform carbon price scenario, between-country variation accounts for 96% of total variation of consumer cost[25].

[24] The importance of incorporating behavioural responses has also been shown in the within-country incidence literature (West and Williams, 2004). Some contributions also incorporate general equilibrium dynamics to estimate the within-country incidence (e.g. Rausch et al., 2011)

[25] Using Equation (6), the variation in cost to consumers h in countries n can be disaggregated as: $\texttt{Var}\left(\hat{\omega}_{n,h}\right) = \texttt{Var}\left(\hat{W}_n\right) + \texttt{Var}\left(\hat{\psi}_h\right)$.

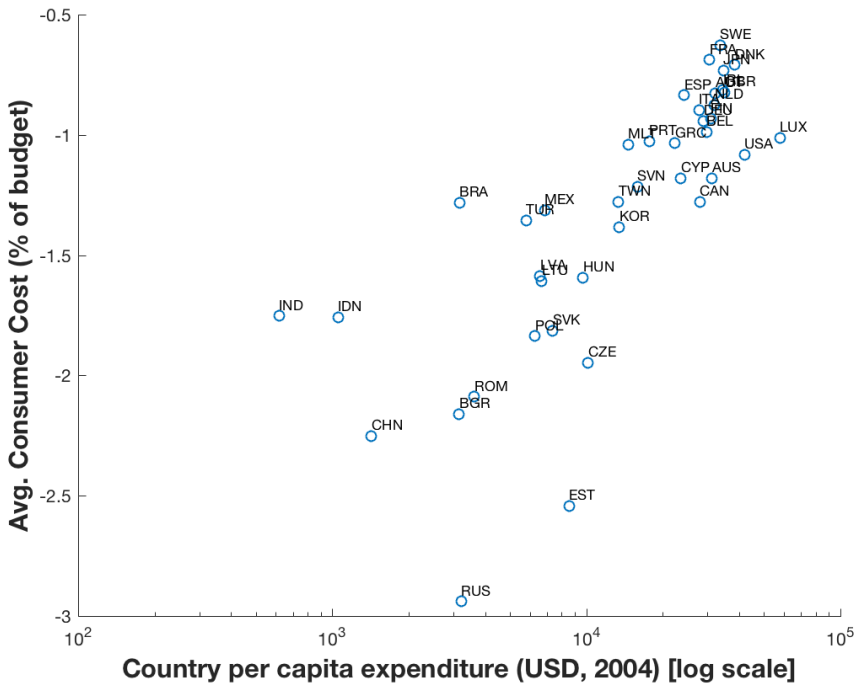
Figure 8: Comparison of global incidence estimates by modelling choice



Notes: This figure shows the global distribution of the consumer cost under a global uniform carbon price of 30 USD per ton of CO_2 simulated in 2004 (40 WIOD countries). The 'full model' replicates the results shown in Figure 2. The 'representative consumer' estimates are from a model that ignores the within-country distribution of incomes. The 'extrapolated' estimates are those from a naive model which calculates the consumer cost based on the observed emissions content of consumption multiplied with the carbon price, ignoring both demand adjustments by consumers and input substitution by producers. The horizontal axis shows percentiles of the income/expenditure distribution across the 4.2 billion inhabitants of the 40 WIOD countries in 2004. The consumer cost is the welfare loss equivalent to losing a share of the total expenditure budget.

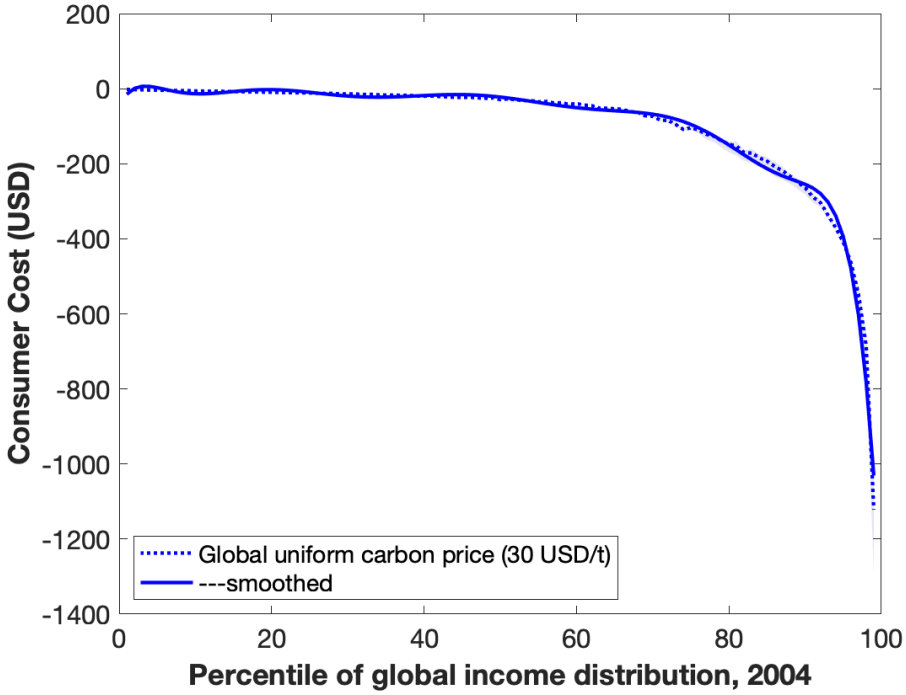
F. Additional figures for main results

Figure 9: Global price of 30 USD/t - Between-country consumer cost



Notes: This figure shows the average consumer cost in each country under a global uniform carbon price of 30 USD per ton of CO_2 simulated in 2004 (40 WIOD countries). The horizontal axis shows average per capita levels of expenditure in each of the 40 WIOD countries in 2004. The consumer cost is expressed as welfare loss (negative values) equivalent to losing a share of the total expenditure budget.

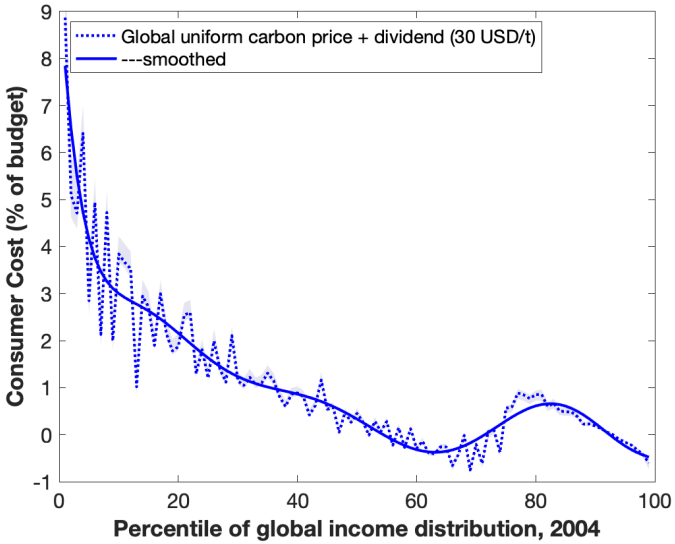
Figure 10: Global price of 30 USD/t - Global distribution of consumer cost (USD)



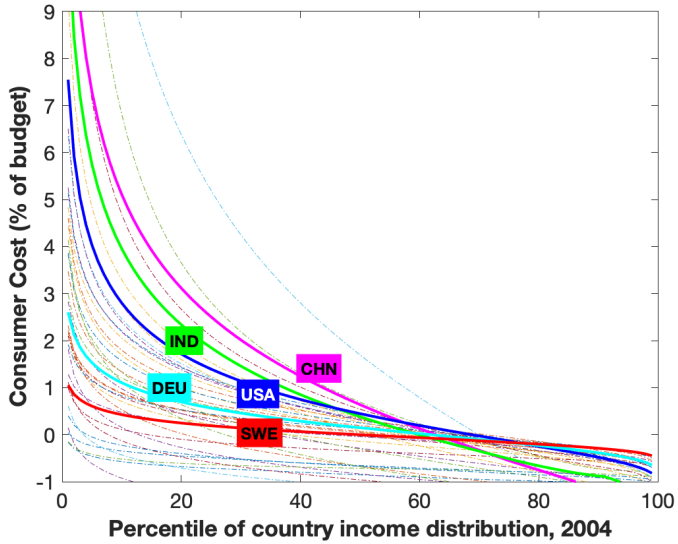
Notes: This figure shows the global distribution of the consumer cost under a global uniform carbon price of 30 USD per ton of CO_2 simulated in 2004 (40 WIOD countries). The horizontal axis shows percentiles of the income/expenditure distribution across the 4.2 billion inhabitants of the 40 WIOD countries in 2004. The consumer cost is expressed as welfare loss (negative values) equivalent USD value (dashed) and approximated with a 10th degree polynomial (solid). Shaded regions are 95% confidence intervals from 500 separate simulations, each using a different set of model parameters drawn from the joint normal distributions for parameter estimates from estimations (15), (16) and (20).

Figure 11: Global price of 30 USD/t and national carbon dividend [consumption tax] - Consumer cost

(a) Global distribution

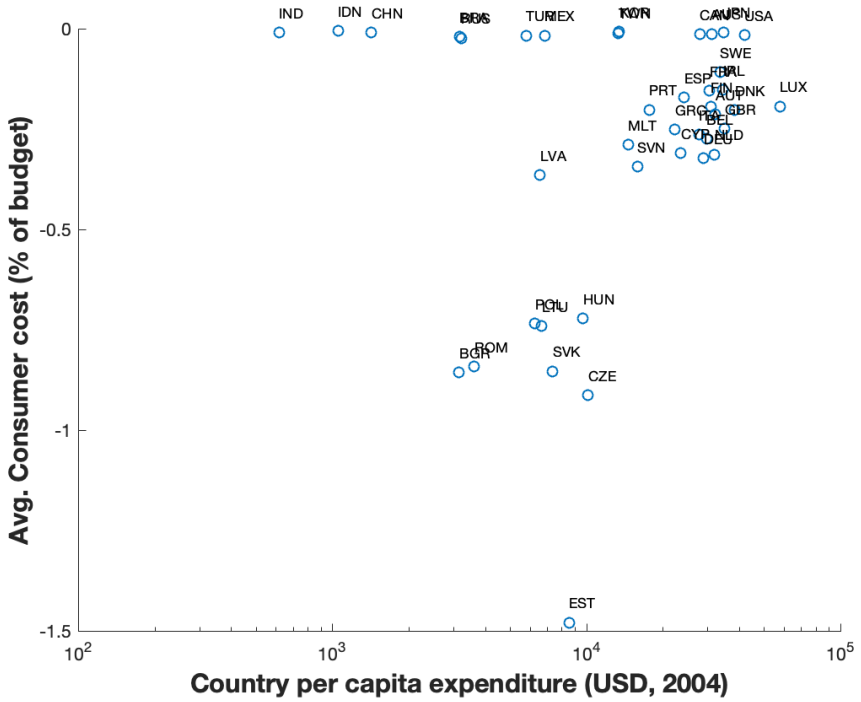


(b) Within-country distribution



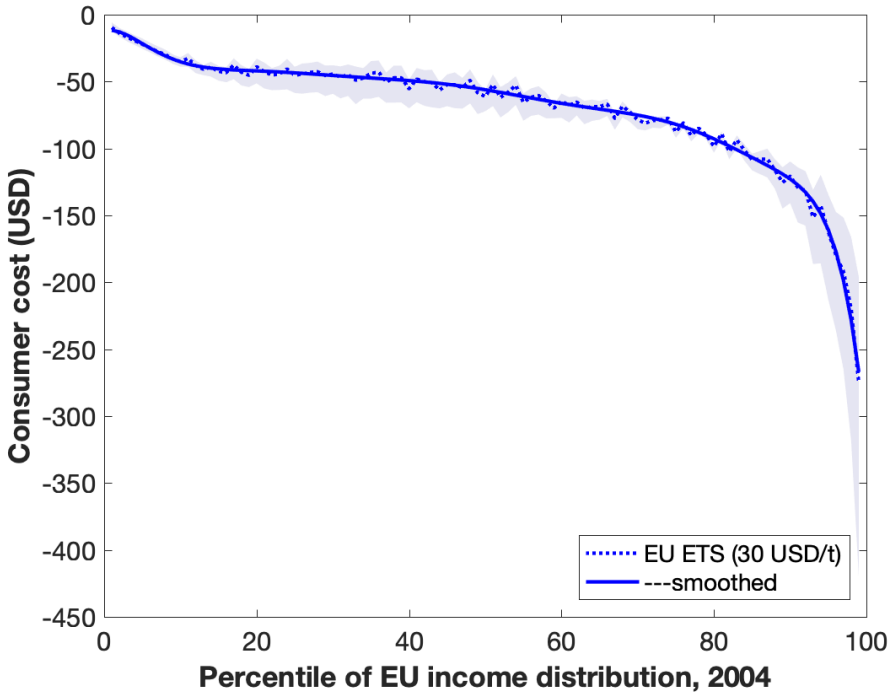
Notes: Consumer cost under a global uniform carbon price of 30 USD per ton of CO_2 simulated in 2004 (40 WIOD countries), net of the benefits from a per capita carbon dividend in each country. Equivalent to Figures 4 and **??**, except that here the revenue is collected (and redistributed) in the country of the consumer, instead of where emissions occur in the value chain. The horizontal axis shows percentiles of the income/expenditure distribution, both globally (Panel a) and within each of the 40 WIOD countries (Panel b) in 2004. Otherwise equivalent to Figure 2 (Panel a) and Figure 3 (Panel b).

Figure 12: EU price of 30 USD/t - Between-country consumer cost



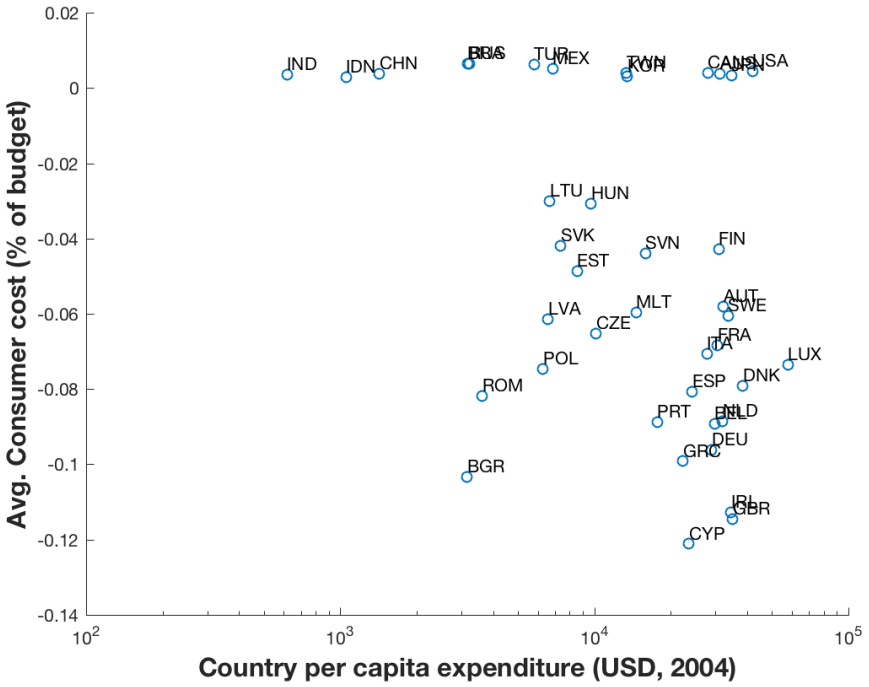
Notes: This figure shows the average consumer cost in each country under an EU-wide (27 countries) carbon price of 30 USD per ton of CO_2, applied to the EU ETS target sectors and simulated in 2004 (model includes 40 WIOD countries). The horizontal axis shows average per capita levels of expenditure in each of the 40 WIOD countries in 2004. The consumer cost is expressed as welfare loss equivalent to losing a share of the total expenditure budget.

Figure 13: EU price of 30 USD/t - EU distribution of consumer cost (USD)



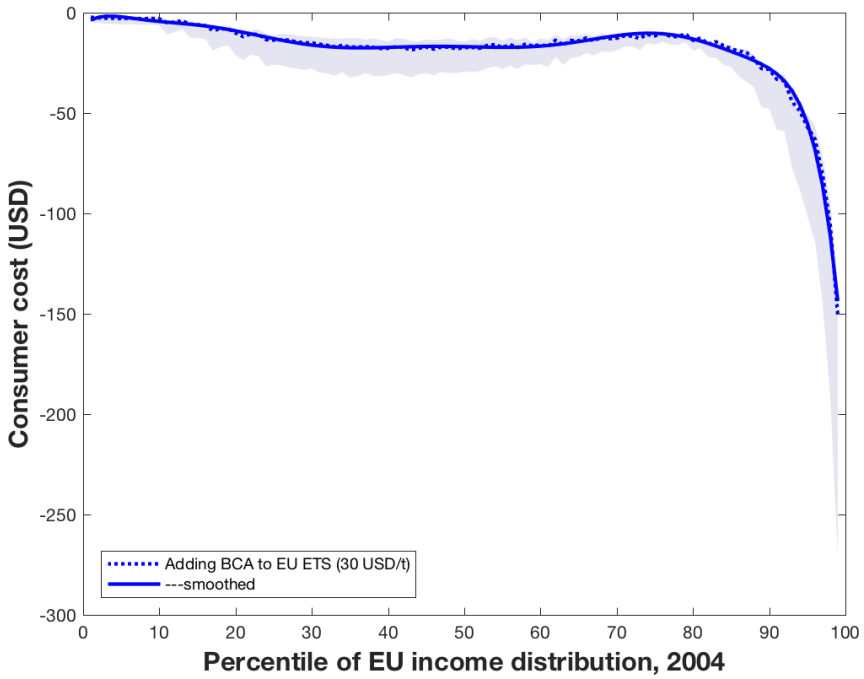
Notes: This figure shows the global distribution of the consumer cost under an EU-wide (27 countries) uniform carbon price of 30 USD per ton of CO_2, applied to the EU ETS target sectors and simulated in 2004 (model includes 40 WIOD countries). The horizontal axis shows percentiles of the income/expenditure distribution across the 490 million inhabitants of the 27 EU countries in 2004. The consumer cost is expressed as welfare loss equivalent USD value (dashed) and approximated with a 10th degree polynomial (solid). Shaded regions are 95% confidence intervals from 500 separate simulations, each using a different set of model parameters drawn from the joint normal distributions for parameter estimates from estimations (15), (16) and (20).

Figure 14: EU Border Adjustment of 30 USD/t - Between-country consumer cost



Notes: This figure shows the average consumer cost in each country under a Border Carbon Adjustment to complement an EU-wide (27 countries) uniform carbon price of 30 USD per ton of CO_2, applied to all sectors and simulated in 2004 (model includes 40 WIOD countries). The horizontal axis shows average per capita levels of expenditure in each of the 40 WIOD countries in 2004. The consumer cost is expressed as welfare loss equivalent to losing a share of the total expenditure budget.

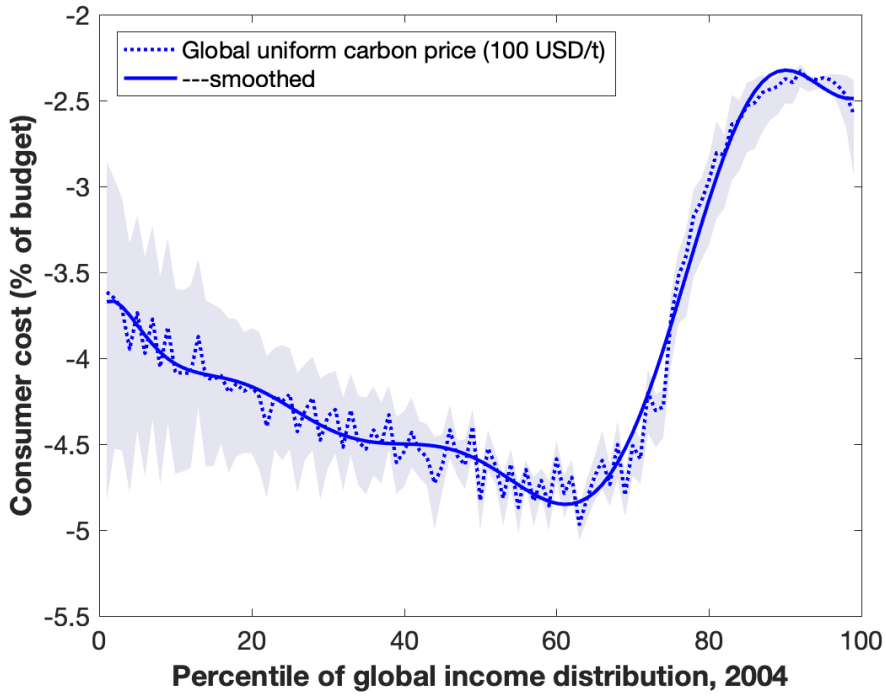
Figure 15: EU BCA of 30 USD/t - EU distribution of consumer cost (USD)



Notes: This figure shows the global distribution of the consumer cost under a Border Carbon Adjustment to complement an EU-wide (27 countries) uniform carbon price of 30 USD per ton of CO_2, applied to all sectors and simulated in 2004 (model includes 40 WIOD countries). The horizontal axis shows percentiles of the income/expenditure distribution across the 490 million inhabitants of the 27 EU countries in 2004. The consumer cost is expressed as welfare loss equivalent USD value (dashed) and approximated with a 10th degree polynomial (solid). Shaded regions are 95% confidence intervals from 500 separate simulations, each using a different set of model parameters drawn from the joint normal distributions for parameter estimates from estimations (15), (16) and (20).

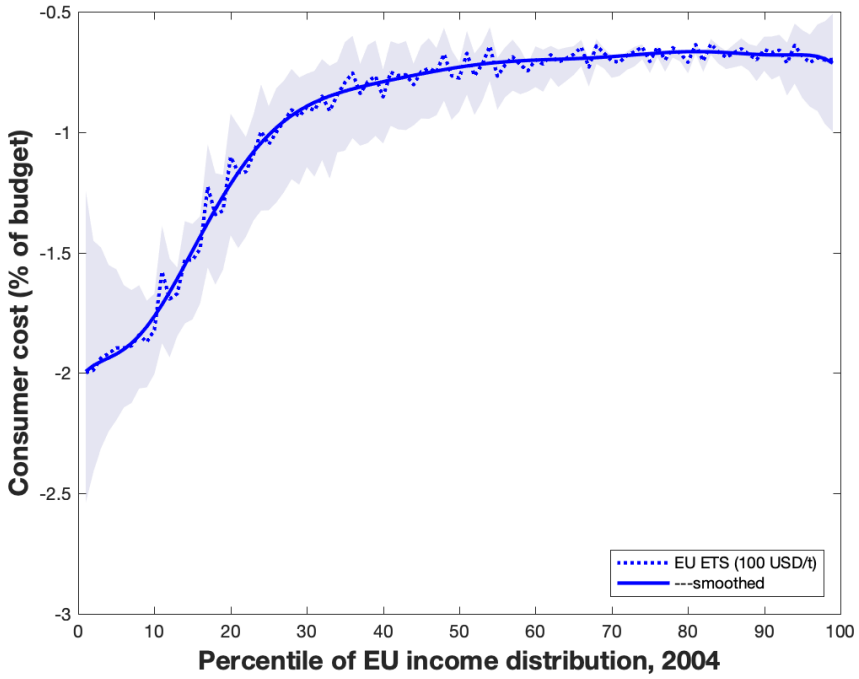
G. Alternative carbon price of 100 USD/t in 2004

Figure 16: Global price of 100 USD/t - Global distribution of consumer cost



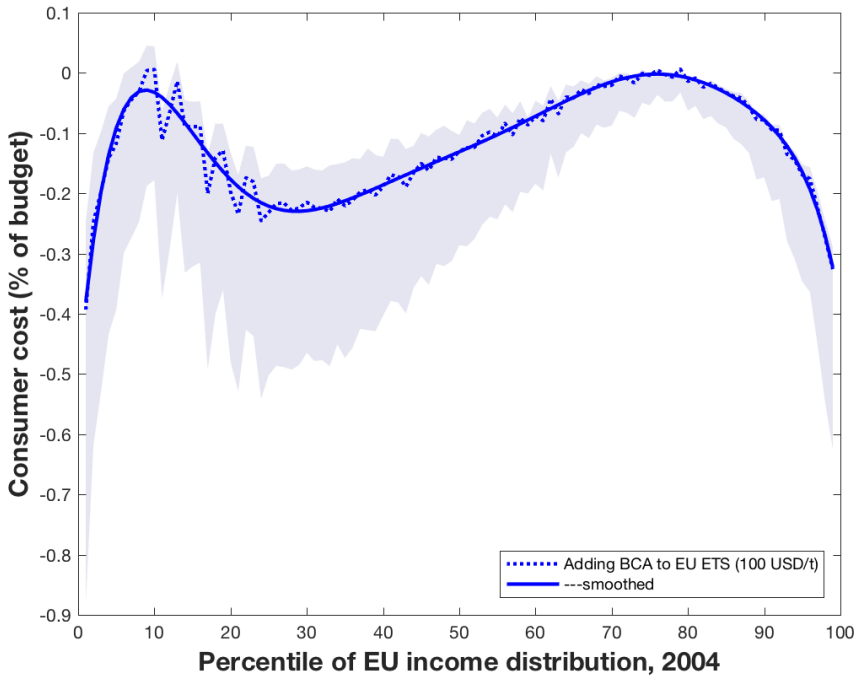
Notes: Same as Figure 2 but with a global uniform carbon price of 100 USD per ton of CO_2 simulated in 2004 (model includes 40 WIOD countries). Global distribution of the consumer cost under a global uniform carbon price. The horizontal axis shows percentiles of the income/expenditure distribution across the 4.2 billion inhabitants of the 40 WIOD countries in 2004. The consumer cost is expressed as welfare loss equivalent to losing a share of the total expenditure budget (dashed) and approximated with a 10th degree polynomial (solid). Shaded regions are 95% confidence intervals from 500 separate simulations, each using a different set of model parameters drawn from the joint normal distributions for parameter estimates from estimations (15), (16) and (20).

Figure 17: EU price of 100 USD/t - EU distribution of consumer cost



Notes: Same as Figure **??** but with an EU-wide (27 countries, ETS sectors targeted) carbon price of 100 USD per ton of CO_2 simulated in 2004 (model includes 40 WIOD countries). The horizontal axis shows percentiles of the income/expenditure distribution across the 490 million inhabitants of the 27 EU countries in 2004. The consumer cost is expressed as welfare loss equivalent to losing a share of the total expenditure budget (dashed) and approximated with a 10th degree polynomial (solid). Shaded regions are 95% confidence intervals from 500 separate simulations, each using a different set of model parameters drawn from the joint normal distributions for parameter estimates from estimations (15), (16) and (20).

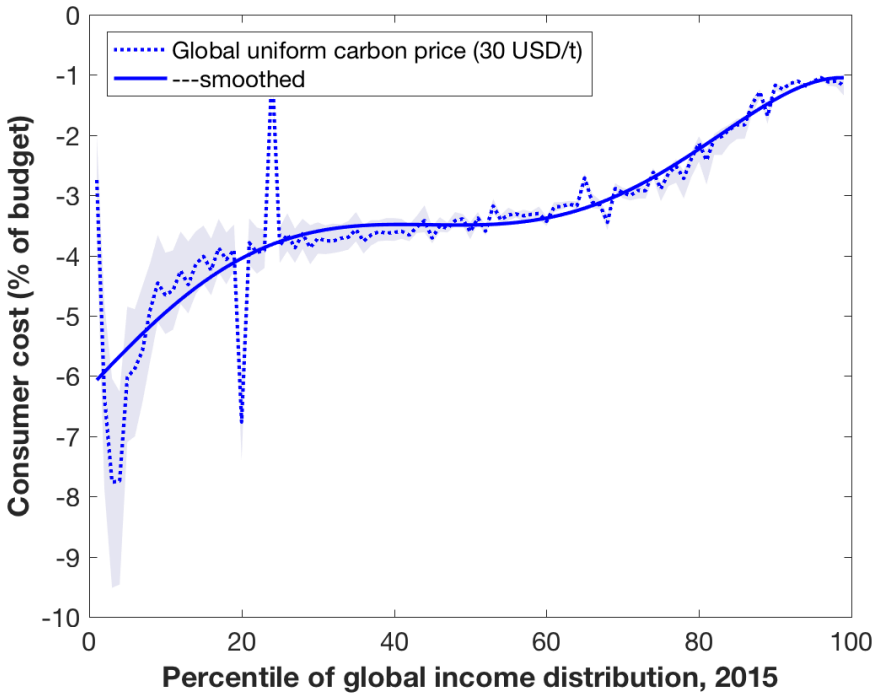
Figure 18: EU BCA of 100 USD/t - EU distribution of consumer cost



Notes: Same as Figure **??** but with a Border Carbon Adjustment to complement an EU-wide (27 countries) uniform carbon price of 100 USD per ton of CO_2 simulated in 2004 (model includes 40 WIOD countries). The horizontal axis shows percentiles of the income/expenditure distribution across the 490 million inhabitants of the 27 EU countries in 2004. The consumer cost is expressed as welfare loss equivalent to losing a share of the total expenditure budget (dashed) and approximated with a 10th degree polynomial (solid). Shaded regions are 95% confidence intervals from 500 separate simulations, each using a different set of model parameters drawn from the joint normal distributions for parameter estimates from estimations (15), (16) and (20).

H. Carbon Price in 189 Countries (Eora) - 2015

Figure 19: Global price of 30 USD/t - Global distribution of consumer cost (Eora)



Notes: This figure shows the global distribution of the consumer cost under a global uniform price of 30 USD per ton of greenhouse gas emissions (CO_2e) simulated in 2015 (189 Eora countries). The horizontal axis shows percentiles of the income/expenditure distribution across the 7.2 billion inhabitants of the 189 Eora countries in 2015. The price is applied to all 189 Eora countries and all greenhouse gases (Kyoto classification) emitted from a large range of activities (including land use). The consumer cost is expressed as welfare loss equivalent to losing a share of the total expenditure budget (dashed) and approximated with a 10th degree polynomial (solid). Shaded regions are 95% confidence intervals from 500 separate simulations, each using a different set of model parameters drawn from the joint normal distributions for parameter estimates from estimations (15), (16) and (20).