Global Tariffs and CO_2

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Abstract

We study the impact of existing worldwide tariffs and several tariff reform schemes on global CO_2 emissions using a multi-country, multi-sector general equilibrium model with detailed input-output linkages. Our analysis reveals the importance of a simple mechanism relating trade policy to global emissions that has not been previously highlighted in the literature: reducing existing tariffs tends to increase emissions primarily by increasing the global output of intermediate inputs relative to final goods. Greater use of intermediates implies, all things equal, more fossil fuel usage and therefore more emissions per unit of global final output. This effect ultimately results from the fact that tariffs are to some extent a tax on material but not on labor. This channel accounts for the majority of the emissions increase from moving to complete liberalization, exceeding even the mechanical effect of increased GDP and overwhelming effects from reallocation of activity across countries and sectors. We find that global partial liberalization schemes that temper this channel – especially by reducing tariff escalation – could achieve substantial global GDP increases with small increases in CO_2 or even emissions reductions.

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1 Introduction

When analyzing solutions to climate change, economists have long studied how policies can reduce greenhouse gases (GHGs) by raising relative prices for GHG intensive goods. Much less attention has been paid to how non-carbon policies may affect GHGs through similar mechanisms. Since substantial near-term cuts in global GHG emissions are necessary to prevent the worst impacts of climate change (IPCC 2018), it is important to understand whether non-carbon policies and reforms of non-carbon policies are working with or against mitigation efforts. Given that trade policy impacts the scale, industrial composition and location of global economic activity and the long literature on the environmental impacts of trade liberalization (see Copeland and Taylor (2004)) it is surprising that the potential effects of existing "non-carbon" tariffs and multilateral tariff reform scenarios on GHG emissions have remained relatively unexplored. This relative neglect mirrors the paucity of work on the effect of tax systems on GHGs more broadly (National Research Council (2013)). In this paper, we contribute to filling this gap by studying the CO_2 impact of existing global tariffs as well as several global tariff reform scenarios.

Our analysis uncovers the importance of a simple mechanism relating trade policy to global emissions that to our knowledge has not been previously highlighted in the trade and environment literature. We find across a range of scenarios that reducing existing tariffs tends to increase emissions primarily by increasing the global output of intermediate inputs relative to final goods. Intuitively, greater use of material implies, all things equal, more fossil fuel usage and therefore more emissions per unit of global final output. This effect is ultimately due to the fact that tariffs are to some extent a tax on material but not on labor, and so their elimination reduces the average global price of intermediate inputs in general and fossil fuels in particular relative to wages. This channel also plays an important role in determining the emissions impact of a variety of alternative trade reform scenarios. While we uncover this channel while studying existing tariffs, we show that this mechanism would also account for a substantial portion of the emissions reductions brought about by tariffs on embodied CO_2. More broadly, this channel is likely to matter in any context where global policies or trends affect the costs of using intermediate inputs vs. labor.

Methodologically, our study uses a multi-country, multi-sector quantitative general equilibrium framework with detailed global input-output linkages that allows us to capture various channels through which tariffs might potentially affect emissions, including reallocation of activity across countries and sectors, and changes in the price of inputs, including fossil fuels. Emissions are generated in the model when fossil fuels are used in either production or consumption. To study the counterfactual effect of removing global tariffs, as well as several other hypothetical tariff reform scenarios, we use the parsimonious "exact hat algebra" methodology from Dekle et al. (2008). We also develop a new decomposition that breaks down the overall effect on emissions into several components in order to understand how tariffs affect CO_2 emissions in a transparent manner. Our decomposition overlaps with but is distinct from the canonical approach in the trade-environment literature (Grossman and Krueger 1993; Copeland and Taylor 1994).

We find that removing global tariffs would increase world GDP by 0.51% points and global emissions by 1.13%, implying that trade liberalization would lead to emissions increases beyond the mechanical "scale" effect of the global output increase. The dominant reason for the emissions increase is that, as noted earlier, tariff removal increases the global output of intermediate inputs by more than GDP, ultimately by reducing the global price of intermediates relative to wages. In our quantification, this channel overwhelms the effects of sectoral reallocation – which *reduces* emissions – and is even more substantial than the scale effect. While our results imply that world trade liberalization would lead to increased emissions that proportionately exceed the output increase, this does not, however, imply that existing tariffs are a desirable mitigation instrument. Indeed, if we value the negative externality from carbon emissions at 50 $\$/tCO_2$, the benefit of the output increase from liberalization exceeds the externality costs by about an order of magnitude.

In addition to complete liberalization, we also examine the emissions consequences of various partial liberalization scenarios. We find that while it technically is possible for tariff liberalization to reduce CO_2, the attainable reductions are small and require tariff rate decreases to be concentrated on the least polluting goods. While more realistic liberalization schemes tend to increase emissions, there is great variability in the CO_2 generated at comparable levels of liberalization. We find liberalization schemes that focus on reducing tariff escalation – the common practice of having higher tariffs on goods that tend to be used more for final consumption than as inputs – can, up to a point, increase global welfare at close to zero or even slightly negative increase in CO_2. This is because such policies limit the labor-intermediate effect by concentrating tariff cuts on goods that are less likely to be used as inputs. We find broadly similar but somewhat weaker effects from partial liberalization schemes that focus on reducing higher initial tariffs. This includes the "Swiss Formula" approach that entails proportionately greater tariff reductions on initially higher tariffs or reducing "tariff peaks" – tariffs that are substantially higher than average. Stepping outside of strictly liberalization scenarios, we find that harmonizing tariffs while keeping average country-level tariffs fixed could lead to significant emissions reductions even while increasing output. We find, however, that the implicit mitigation cost of the tariff increases that are part of such a harmonization would comfortably exceed the benefits at standard externality valuations.

Our work complements a substantial quantitative literature on trade and the environment. Much of this literature focuses on how trade affects the environment through re-allocation of production across countries and industries (Copeland and Taylor 1994; Frankel and Rose 2005; Levinson 2009; Shapiro 2016).[1] Another large branch of the literature is on trade liberalization and the environment (e.g. Grossman and Krueger (1993), Antweiler et al. (2001), Cherniwchan (2017)), although these papers do not typically focus on CO_2. Those papers that do focus on trade policy and CO_2, in keeping with this broader emphasis on re-allocation, almost all focus on hypothetical carbon tariffs, which by design are meant to tax more polluting activities and regions.[2] Two recent papers that are closer to ours in emphasizing "non-carbon" tariffs (Pothen and Hübler (2018) and Shapiro (2019)) – discussed in more detail below – also focus on either the regional or sectoral heterogeneity in the effect of tariffs. In contrast to this existing work, we uncover a different mechanism through which tariff changes could affect environmental outcomes that is largely independent of the composition of tariff rates, namely the fact that tariffs are to some extent a tax on intermediates but not on labor. We also elaborate on how various tariff reform scenarios would have different CO_2 consequences depending on how this mechanism is managed.

As noted above, there are to our knowledge two other papers that focus on the effects of global "non-carbon" tariffs on emissions. Pothen and Hübler (2018) use a quantitative general equilibrium model to study the interaction between trade policy and climate, and find that reductions in tariffs and iceberg costs would reduce emissions in several regions even while increasing global emissions. Our quantitative results are comparable to theirs but we highlight the central role of the labor-intermediate channel in explaining global emissions increases, and we also study what type of partial liberalization scenarios are likely to lead to more or less severe CO_2 implications. Shapiro (2019) provides evidence that current trade policy has a negative environmental bias because trade barriers are substantially lower on dirtier relative to cleaner goods, a pattern which can be generated by tariff escalation. He then uses quantitative general equilibrium analysis to show that various forms of mean preserving tariff harmonization that would undo this negative bias could simultaneously increase global output and decrease emissions. Shapiro's work focuses on the composition of tariffs across goods, whereas we highlight a channel – dominant in our quantification – that arises from the fact that tariffs apply on material but not labor, rather than from tariff

[1] Of this work Shapiro (2016) is most related to ours because it focuses on greenhouse gases.

[2] Most of these analyses rely on GTAP or similar large scale general equilibrium models. See Böhringer et al. (2012) and Branger and Quirion (2014) for reviews or Böhringer et al. (2015) for a more recent example. Methodologically, among the carbon tariff papers, our paper is most closely related to Larch and Wanner (2017), who use a structural gravity model and the exact-hat algebra methodology.

differences across goods. We should note, however, that the negative relationship between tariffs and embodied emissions that Shapiro documents is also present in our data, and we also obtain quantitative effects of comparable magnitude from similar tariff harmonization. We find that the tariff increases that are part of the mean preserving harmonization are essential for the emissions reductions, partially by raising the relative prices of intermediates, and that the implicit mitigation costs of these increases would exceed their benefits.

Beyond the trade and environment literature, our work also contributes to the broader question of the effect of non-carbon policies on GHGs. As noted in National Research Council (2013), there is limited research on how non-carbon policies, other than energy related policies, influence GHG emissions. In contrast to our findings for tariffs, exploratory work in this report finds that broad-based tax incentives in the US influence GHGs almost exclusively through changes in GDP. Our analysis suggests that an important factor in whether a non-carbon policy may affect CO_2 levels is the extent to which the policy functions as a tax on intermediate inputs. We demonstrate, that this mechanism is likely to be very relevant in the context of other taxes that partly function as turnover taxes.[3]

The rest of this paper is structured as follows. Section 2 presents the theoretical model used for our quantification exercise. Sections 3 discusses our data sources and some descriptive statistics. Sections 4 through 6 present and analyze our results and Section 7 concludes.

2 Model

2.1 Basic Setup

Our quantitative framework is an Armington (1969) model with N countries and S sectors or goods. Each country potentially produces its own variety of every good and these goods are traded internationally subject to trade costs and tariffs. The preferences of each countries' representative consumer are assumed to be Cobb-Douglas over the S goods and constant elasticity of substitution (CES) between varieties of each good. On the production side, firms produce under perfect competition and constant returns to scale with labor and intermediate goods with Cobb-Douglas technology. CO_2 emissions are generated by the use of fossil fuels in production and consumption. We treat CO_2 as a pure externality – so consumers take CO_2 levels as given – that generates disutility in an additively separable from utility from

[3] This would include sales taxes, which in practice are known to function as a tax on business inputs, with sales taxes on business inputs accounting for over 40 % of total US sales taxes (Phillips and Ibaid 2019). It would even apply to some extent to value-added taxes, which can function as a tax on inputs in countries with weaker tax administration (Ebrill et al. 2001; Sharma 2020)

consumption.[4]

2.1.1 Firms

Perfectly competitive firms produce using labor and an intermediate input bundle, with the production function given by:

$$Y_i^s = A_i^s \left(L_i^s\right)^{\alpha_i^s} \left(M_i^s\right)^{1-\alpha_i^s},$$

where A_i^s is a productivity parameter; M_i^s is an intermediate input aggregate; and α_i^s is the Cobb-Douglas labor share, which varies by country and sector. Given that tariffs act as implicit taxes on intermediate inputs, the functional form assumption between labor and intermediate inputs is particularly important. Estimates from the literature suggest that assuming Cobb-Douglas is reasonable (Atalay 2017). We assume that M_i^s is itself a Cobb-Douglas aggregator of an intermediate input bundle for each sector s:

$$M_i^s = \prod_{\tilde{s}} \left(m_i^{\tilde{s}s}\right)^{\omega_i^{\tilde{s}s}},$$

where $\omega_i^{\tilde{s}s}$ is the share of intermediate inputs in sector s that originate from sector $\tilde{s}$; $m_i^{\tilde{s}s}$ is a CES aggregate that is assumed to be identical to the one for consumption and so has a price of $P_i^{\tilde{s}}$. The price of the index depends on the used sector but is the same across all using sectors. With this formulation, the factory gate price of s from i will be the Cobb-Douglas unit cost function, and the price at destination j will also take into account transportation costs and tariffs. This gives us a destination price of:

$$p_{ij}^s = \frac{1}{A_i^s}\overline{\alpha}_i^s \left(\frac{w_i}{\alpha_i^s}\right)^{\alpha_i^s} \left[\frac{1}{1-\alpha_i^s}\prod_{\tilde{s}}\left(\frac{P_i^{\tilde{s}}}{\omega_i^{\tilde{s}s}}\right)^{\omega_i^{\tilde{s}s}}\right]^{1-\alpha_i^s} d_{ij}^s \left(1+\tau_{ij}^s\right), \tag{1}$$

where $\overline{\alpha}_i^s \equiv \left[\left(\frac{\alpha_i^s}{1-\alpha_i^s}\right)^{1-\alpha_i^s} + \left(\frac{1-\alpha_i^s}{\alpha_i^s}\right)^{\alpha_i^s}\right]$; w_i is the wage in country i; $P_i^{\tilde{s}}$ is the CES price index for $\tilde{s}$ in i (given below); $\prod_{\tilde{s}}\left(\frac{P_i^{\tilde{s}}}{\omega_i^{\tilde{s}s}}\right)^{\omega_i^{\tilde{s}s}}$ is the price of the intermediate input bundle for sector s in country i; $d_{ij}^s \geq 1$ is the iceberg transportation cost of delivering a good from i to j; and τ_{ij}^s is the ad-valorem tariff rate faced by the product. Note that in the case where $i = j$, the tariff rate will be equal to zero, i.e. $\tau_{ii}^s = 0$.[5] The CES price index is:

$$P_j^s = \left[\sum_k \alpha_k {p_{kj}^s}^{1-\epsilon^s}\right]^{\frac{1}{1-\epsilon^s}} \tag{2}$$

[4] We therefore report changes in real income and changes in damages from CO_2 emissions separately.

[5] As we discuss in the data section, we do aggregate some groups of very small countries. In such cases, the average internal tariff could be positive.

Given these assumptions, the expenditure of firms in j producing t on s from i is:

$$X_{ij}^{st} = \lambda_i \left(\frac{p_{ij}^s}{P_j^s}\right)^{1-\epsilon^s} \left[\left(1-\alpha_j^t\right)\omega_j^{st} X_j^t\right], \tag{3}$$

where λ_i is a quality or taste parameter for i's product; and $X_j^t = \sum_i X_{ji}^t$ is defined as the total sales value of sector t in country j.

2.1.2 Households

Household expenditure in j on i's variety of good s is:

$$X_{ij}^{sC} = \lambda_i \left(\frac{p_{ij}^s}{P_j^s}\right)^{1-\epsilon^s} \beta_j^s X_j, \tag{4}$$

where β_j^s is the Cobb-Douglas share of household consumption on good s in country j; and X_j is the total expenditure on all goods in country j. Using (3) and (4), the total expenditure in j on s from i is therefore:

$$X_{ij}^s = \alpha_i \left(\frac{p_{ij}^s}{P_j^s}\right)^{1-\epsilon^s} \left\{\beta_j^s X_j + \sum_t \left(1-\alpha_j^t\right)\omega_j^{st} X_j^t\right\} \tag{5}$$

Note that this expression also holds when $i = j$, i.e. when we consider the expenditure of country j on its domestic variety.

2.1.3 Equilibrium

The model is closed by two equilibrium conditions. First, the total expenditure by country j households has to be equal to household income, which includes wage income, rebated tariff revenues and an exogenous trade imbalance term:

$$X_j = w_j L_j + \sum_s \sum_m \tau_{mj}^s \frac{X_{mj}^s}{1+\tau_{mj}^s} + D_j, \tag{6}$$

where L_j is the labor endowment of country j; $\sum_s \sum_m \tau_{mj}^s \frac{X_{mj}^s}{1+\tau_{mj}^s}$ is the tariff-inclusive level of net imports; and D_j is aggregate net imports in j, which is assumed fixed.

The second equilibrium condition requires the total wages paid in country i to be equal to the revenue in each sector scaled by the labor share of the industry in that country:

$$\sum_s \sum_j \alpha_i^s \frac{X_{ij}^s}{1+\tau_{ij}^s} = w_i L_i, \tag{7}$$

Here, $\alpha_i^s \frac{X_{ij}^s}{1+\tau_{ij}^s}$ is the payment to labor that accrues from i's sales of s to j.

2.2 Proportional Changes

This multi-sector Armington model features large number of parameters, including various preference, productivity and transportation cost parameters. Following the "exact hat algebra" methodology of Dekle et al. (2008), it is possible to drastically reduce the number of parameters needed in order to evaluate the effect of a change in global tariffs. Once this method is applied, the only parameters we require are the trade elasticities for each sector and various Cobb-Douglas parameters that can be calculated directly as shares in the data. The basic approach is to focus on the proportional change in a given variable relative to the baseline value. For example, if the variable of interest were X_{ij}^s, we will use $\hat{X}_{ij}^s \equiv X_{ij}'^s / X_{ij}^s$, where $X_{ij}'^s$ is the counterfactual value of X_{ij}^s.

The proportional change formulations for the key expressions of the model are as follows:

$$\hat{p}_{ij}^s = (\hat{w}_i)^{\alpha_i^s} \left[\prod_{\tilde{s}} \left(\hat{P}_i^{\tilde{s}} \right)^{\omega_i^{\tilde{s}s}} \right]^{1-\alpha_i^s} \hat{T}_{ij}^s \tag{8}$$

$$\hat{P}_j^s = \left[\sum \frac{X_{kj}^s}{X_j^s} \left(\hat{p}_{kj}^s \right)^{1-\epsilon^s} \right]^{\frac{1}{1-\epsilon^s}} \tag{9}$$

$$\hat{X}_{ij}^s = \frac{X_{ij}^{sC}}{X_{ij}^s} \left(\frac{\hat{p}_{ij}^s}{\hat{P}_j^s} \right)^{1-\epsilon^s} \hat{X}_j + \sum_t \frac{X_{ij}^{st}}{X_{ij}^s} \left(\frac{\hat{p}_{ij}^s}{\hat{P}_j^s} \right)^{1-\epsilon^s} \hat{X}_j^t \tag{10}$$

$$\hat{X}_j = \phi_j^w \hat{w}_j + \phi_j^D + \sum_s \sum_m \frac{X_{mj}^s}{X_j} t_{mj}'^s \hat{X}_{mj}^s \tag{11}$$

where $\hat{T}_{ij}^s = \frac{1+\tau_{ij}'^s}{1+\tau_{ij}^s}$, $t_{mj}'^s = \frac{\tau_{mj}'^s}{1+\tau_{mj}'^s}$ and ϕ_j^w and ϕ_j^D are the baseline shares of country j's income coming from labor and the exogenous trade imbalance, respectively. Equations (8)-(11) and (7) determine counterfactuals. Equations (8) and (9) determine price levels for a given wage vector, while the remaining conditions determine wages.[6] We lay out the full solution algorithm in the appendix.

2.3 Emissions

We assume that emissions are generated by the use fossil fuels in production and consumption. By accounting for emissions at the fossil fuel-sector level, we are able to capture that in some sectors fossil fuels are used as a feedstock as opposed to being combusted (e.g. crude oil used in crude oil refining or natural gas in chemical manufacturing). Specifically, the use of each unit of an input s in country j by sector t – where $t = C$ for household use

[6] We normalize the global wage: $\sum_j \hat{w}_j L_j = \sum_j L_j$.

– creates emissions equal to κ_j^{st}. Note that while this is defined for all values of s, it will only be non-zero for fossil fuels. The emissions generated in country j by sector t's use of i's variety of good s are then:

$$\Phi_{ij}^{st} = \kappa_j^{st} \frac{X_{ij}^{st}}{p_{ij}^{s}} \tag{12}$$

We can obtain global emissions by summing across country-pairs, used sectors and using sectors:

$$\Phi = \sum_i \sum_j \sum_s \sum_t \frac{X_{ij}^{st}}{p_{ij}^{s}} \kappa_j^{st} \tag{13}$$

The proportional change in emissions can then be written as:

$$\hat{\Phi} = \sum_i \sum_j \sum_s \sum_t \frac{\Phi_{ij}^{st}}{\Phi} \frac{\hat{X}_{ij}^{st}}{\hat{p}_{ij}^{s}}$$

The key share here is the share of emissions generated by the *use* of product s from country i by sector t in country j in the baseline. Again, this will be equal to zero for most used sectors.

2.3.1 Emissions decomposition

Our quantitative analysis will emphasize a new decomposition of emissions changes into multiple channels that will help interpret our results. We develop a decomposition that overlaps with but is distinct from the standard approach from Copeland and Taylor (1994), which breaks down emissions changes into scale, composition and technique effects. We first present a Copeland and Taylor style decomposition following Cherniwchan et al. (2017) using our notation before introducing our new approach. We report the results of both decompositions for a range of counterfactuals in the Appendix.

The conceptual starting point for the standard decomposition is to think in terms of the emissions generated per value-added output of an industry. Global emissions can be written as:

$$E = \sum_j \sum_s k_j^s V_j^s \tag{14}$$

Taking the log and differentiating, we obtain:

$$\frac{dE}{E} = \frac{dV}{V} + \sum_j \sum_s \frac{E_j^s}{E} \frac{d\left(V_j^s/V\right)}{\left(V_j^s/V\right)} + \sum_j \sum_s \frac{E_j^s}{E} \frac{dk_j^s}{k_j^s} \tag{15}$$

The first term is the scale effect, which captures the mechanical effect of greater economic output (i.e. GDP) on emissions. The second term – the composition effect – captures the effect of reallocation of value-added output across country-sectors with different emissions per value-added. The third term – the technique effect – captures changes in the emissions per value-added output of a given country-sector.

The starting point of our decomposition is to think in terms of the emissions generated through the use of fossil fuels by a sector or by households rather than in terms of the emissions generated per value-added output. This starting point is more directly related to how emissions are generated in both the data and the model, i.e. on the basis of fossil fuel use. It has the additional advantage of naturally allowing emissions from household consumption to be included, in contrast to the standard approach. To implement the decomposition, we start by writing global emissions as the sum of the emissions generated through the use of fossil fuels at every level:

$$E = \sum_j \sum_s \sum_t \kappa_j^{st} Q_j^{st}$$

where Q_j^{st} is the value of the good being used deflated by its own price level.[7] Taking the log and differentiating as before, we get:

$$\frac{dE}{E} = \frac{dQ}{Q} + \sum_j \sum_s \sum_t \frac{E_j^{st}}{E} \frac{d\left(Q_j^{st}/Q\right)}{Q_j^{st}/Q} \tag{16}$$

In our setup, κ_j^{st} is a constant and so there is no term corresponding to a change in these coefficients. The first term here resembles a scale effect but it actually captures changes in global *gross* output rather than in global final output (i.e. GDP). While we could stop here and have a decomposition in two terms, it is natural to still include a standard scale effect that would help us distinguish the effect of a mechanical increase in global GDP from effects that arise because each unit of global GDP causes more or less emissions. To do this, we simply split the gross output effect as follows:

$$\frac{dE}{E} = \frac{dV}{V} + \frac{d\left(Q/V\right)}{Q/V} + \sum_j \sum_{s \in E} \sum_t \frac{E_j^{st}}{E} \frac{d\left(Q_j^{st}/Q\right)}{Q_j^{st}/Q} \tag{17}$$

We now have three terms. The first is the standard scale effect. The second captures emissions changes that are due to an increase in gross output relative to final output. Since gross output is equal to final output plus intermediate input purchases, this term can equivalently be thought of as capturing changes in intermediate inputs as a share of

[7] The using index t could capture either the using industry or household use. As for the used good index, s, only the fossil fuel goods have positive emissions.

gross output. Intuitively, if the same final output is produced using more intermediate inputs, all things equal, this implies more fossil fuel usage and therefore more emissions. The third term captures the effects of a reallocation in the use – both firm and household – of different goods across countries and sectors. We refer to this term as the "reallocation" effect to distinguish it from the standard composition effect, which captures changes in value added shares across countries and sectors. The second two terms together capture effects through changes in a global emissions factor that maps global GDP to emissions, and by construction are equivalent to the sum of the composition and technique effects in the standard decomposition.

Although we have presented the algebra of our decomposition here using a differentiation approach for comparison to the standard approach in the literature, it will be more natural in our actual implementation to use a proportional change version of our decomposition. The algebra for the proportional change version provides exact log changes for each effect rather than differential terms, and therefore also has a scale effect that matches exactly the log change in global output between the baseline and counterfactual. The algebra for the proportional change decomposition is provided in the appendix.[8]

3 Data

Baseline Data

Baseline values for bilateral trade flows, country input-output tables and CO_2 emissions are from the GTAP 9.0 database for the benchmark year of 2011 (Aguiar et al. 2016). We aggregate the database to 129 regions (Table A.2) and 20 sectors (Table A.1). Our sector aggregation follows Shapiro (2019). Each fossil fuel (coal, crude oil, natural gas, refined petroleum) is kept as a single sector, while the remaining sectors are aggregated.

The value added (α_j^s) and intermediate input (ω_j^{st}) expenditure shares can be directly calculated from the GTAP database.[9] Gross output for each country-sector is the sum of pre-tariff bilateral trade flows across destination countries. Value added is gross output minus expenditures on intermediate inputs. The GTAP database reports total CO_2 emissions from the use of each fossil fuel in each sector and final consumption.[10] We winsorize emissions per

[8]In practice, the two approaches yield almost identical results. We report our two decomposition approaches as well as the Copeland and Taylor style decomposition for a range of counterfactuals in the Appendix.)

[9]We winsorize value added shares at 1.5%. Only a small fraction (1.4%) of the value added shares are affected by the winsorization.

[10]These emissions measures capture only energy related CO_2 emissions, which account for roughly 65% of global GHG emissions (`https://www.epa.gov/ghgemissions/`

dollar values that are above the 95th percentile within each fossil fuel. This affects only 1% of fossil fuel-sector pairs, and mainly those pairs that have very small values. By accounting for emissions at the fossil fuel-using sector level, we are able to capture that in some sectors fossil fuels are used as a raw material as opposed to a fuel (e.g. crude oil used in crude oil refining or natural gas in chemical manufacturing).

Trade Elasticities

We conduct our analysis with two alternative sets of trade elasticities, which yield very similar results. The baseline results we report use elasticities from the GTAP database and are reported in the first column of Table 1. The elasticities range from 1.80 for minerals to 31 for natural gas. The elasticities are generally relatively high for fossil fuels. As an alternative case we use the trade elasticities reported in Shapiro (2019), who takes the median estimate across four studies that estimate these elasticities, after aggregating estimates within each study using inverse variance weighting. We also explore the impacts of proportionally increasing and decreasing the trade elasticities to better understand the importance of these parameters.

3.1 Summary Statistics

Table 1 also provides information about several baseline values of interest by sector. The sectors vary substantially in terms of total value (second column of numbers) and in terms of the fraction of output that is traded (third column of numbers). The share of intermediate input usage to total output value also varies dramatically (fourth column of numbers). The lowest intermediate input share is for crude oil (0.2), which is a raw commodity, while the highest is for petroleum products (0.85), since refining is a reasonably direct conversion of crude oil into other products. With the exception of the latter, fossil fuels tend to have lower intermediate input shares than most manufacturing industries.

In the next three columns, we attribute CO_2 to sectors using three measures, each of which provides a reasonable way to quantify a sector's contribution to global CO_2. Used CO_2, fourth column of numbers, measures emissions due to the use of that sector's output by households and by other sectors. Since emissions are generated by the use of fossil fuels, these values are zero for all other sectors. Coal use is the largest source of global emissions followed by petroleum products and natural gas. Notice that unlike coal, petroleum and

`global-greenhouse-gas-emissions-data`). We do not include non-energy related greenhouse gas emissions, such as those from land use and agriculture, due to limitations in calibrating these emissions channels at a global scale.

natural gas, crude oil itself does not account for a substantial amount of used emissions because crude oil is generally used as a source of energy only after being refined.

Using CO_2 measures direct emissions from the use of fossil fuels by each using sector. As expected, transportation and electricity production are the largest sources of emissions. Embodied CO_2, captures the total emissions generated by the final consumption of a sector's output, taking into account the emissions generated by all downstream activities. This measure therefore accounts for direct emissions in production plus the emissions from the inputs used in production, and the inputs used in the production of those inputs, etc. We calculate embodied emissions at the country-sector level based on the model's accounting identities (see Section A.3 for details). The embodied emissions are much more balanced across sectors than the direct and using emissions because the embodied emissions spread the emissions from electricity and transportation to the sectors that use these goods as intermediate inputs. Hence, a sector such as equipment manufacturing which does not directly use a substantial amount of energy goods but is likely to use electricity and other inputs has a relatively high embodied CO_2 level even while having low using CO_2.

Shapiro (2019) emphasizes the "negative environmental bias" in the structure of existing tariffs, whereby tariffs are higher on goods with lower embodied CO_2. This pattern is also present in our data. In Figure 1 we plot average embodied emissions on average tariffs by sector. In general it is clear that industries with higher embodied emissions tend to face lower tariff rates. This pattern is present in simple average tariff rates and in effective tariff rates, which are the changes in the sector price indices when tariffs are removed.[11] We should therefore expect that policies that eliminate or harmonize tariffs would cause a relative reallocation away from carbon intensive goods.

Table 2 reports baseline GDP, output, intermediate input share and CO_2 for the top 20 emitting countries. Emissions are allocated by both using sector and by embodied emissions, which reflects countries' consumption patterns. The top 20 emitting countries comprise around 80% of total global emissions and GDP. China and the US are by far the top two contributors to CO_2. When allocating by using sector, China is a far bigger contributor than the US (6,735 to 4,151 million tons). However, when allocating by embodied emissions China and the US are nearly identical. This suggests that a large fraction of China's CO_2 emissions are generated producing goods that are consumed elsewhere, and that the US imports a large fraction of polluting goods. The intermediate input shares are generally around 0.5, although China has a notably high intermediate share (0.66), while Saudi Arabia has a notably low

[11] We also confirm this pattern through a more formal regression analysis at the country-sector level. Consistent with Shapiro (2019), we find that the negative relationship between tariffs and embodied CO_2 is driven by industry- rather than country-level variation. These results are available in the Appendix (A.4).

share (0.36). The final two columns report embodied CO_2 rates and average tariffs. Unlike in the sector averages, there is no obvious pattern relating these two values.

4 Results – Tariff Removal

In order to understand how current tariffs affect global emissions, it is natural to consider the counterfactual effect of removing all existing tariffs. We present the impacts of global tariff removal on CO_2 emissions and real GDP in the first column of results in Table 3. Removing global tariffs increases global CO_2 by 1.03% and increases real income by 0.47%.[12] That the increase in emissions is greater than the increase in output points to an increase in the emissions generated per unit output as tariffs are removed.

Our decomposition provides greater detail on the effects that underlie the change in CO_2 (rows 2-4). The scale effect is 0.47%, or equal to global increase in real income, and captures the purely mechanical increase in emissions due to the output increase. The difference between the change in CO_2 and the scale effect, 0.56%, is effectively the increase in the global emissions factors. The second and third terms in the decomposition laid out in Equation (17) break this increase into two additional channels.

The second channel is the labor-intermediate effect, which accounts for 1.07%. This term captures an increase in value (i.e. gross output) relative to value-added (i.e. final output) as a result of removing tariffs. When the same amount of final output is produced with more intermediate inputs relative to labor, more emissions will result, all else equal, because the use of intermediate inputs – of which fossil fuels are a subset – generates emissions but the use of labor does not. Tariffs are applied on intermediate inputs, at least to some extent, but not on labor and therefore their removal reduces the price of intermediate inputs relative to wages. This is captured by the change in the global price index in Table 3. Since we choose global wages as the numeraire, the 1.18% reduction in the price level captures the fact that goods have become cheaper relative to labor as a result of tariff removal.

The third channel, the reallocation effect, has a value of -0.51% and therefore works to *reduce* emissions. This is consistent with the fact that existing tariffs tend to be higher on cleaner goods, as discussed in the previous section in connection with Figure 1 and as emphasized by Shapiro (2019). When tariffs are removed, the resulting reallocation of activity across sectors and countries therefore works to undo some of the emissions increases that we see through the scale and labor-intermediate effects.

While the foregoing analysis emphasizes a comparison between percentage changes in output vs. emissions as a natural way of thinking about the effects of tariffs on CO_2, we

[12] In our framework, the global EV numbers are equivalent to the change in global real GDP.

should note that this does not directly tell us anything about welfare in general. Indeed, if we value the global CO_2 externality at 50 $/t$CO_2$, the CO_2 cost of moving to global free trade would be equal to about $15 billion, which is substantially less than the $324 billion equivalent variation gains. Put differently, while current tariffs reduce emissions, they do so at a tremendous cost of about 1000 $/t$CO_2$.

4.1 Regional Heterogeneity

Our global analysis reveals that tariffs depress emissions, especially through the labor-intermediate channel. In this section, we explore the regional heterogeneity in these results. To begin we report results from separately removing OECD and non-OECD country tariffs in the last two columns of Table 3. It is clear that the large emissions increases due to the global removal are especially connected to the non-OECD tariffs, whoose removal increases emissions substantially more than the scale effect. By contrast, the OECD tariff elimination actually increases output by more than emissions in percentage terms. Despite these considerable differences in emissions outcomes, the labor-intermediate channel that we especially highlight in this paper is substantially larger than the scale effect for both groups of countries. Notably, the reallocation effect tempers the scale and labor-intermediate effect substantially for OECD but not non-OECD countries. Table 3 also reports the equivalent variation and emissions changes in OECD vs. non-OECD countries under all of the scenarios we consider. Notably, non-OECD tariff removal increases emissions by about as much in OECD countries as it does in non-OECD countries. This reflects the increased output in OECD countries under this counterfactual, as shown by the OECD equivalent variation row of Table 3.

We further explore this regional heterogeneity by evaluating unilateral tariff removal counterfactuals (e.g. individual countries set all tariffs to zero). We report results for these counterfactuals for the top 20 countries by baseline emissions in Table 4. Although emissions increase for only about half of these countries, the labor-intermediate effect is always positive and generally larger in magnitude than the scale effect. Removal of US tariffs would increase global emissions by 0.03%, and the vast majority of this increase would take place in other countries. The major driver of these emissions increases is the labor-intermediate channel, which is almost as large as the scale effect while the reallocative effects negate each other. The elimination of Chinese tariffs increases global emissions by much more, about 0.14%. Relative to the US, a much larger share of the emissions increases would take place within China. We see rather different patterns in a few countries, most notably Japan and India, where tariff removal would *reduce* global emissions. For both countries, this is the case because the labor-intermediate channel is relatively modest while the reallocation effect substantially contribute to lower emissions. Overall, the labor-intermediate channel shows up in a remarkably consistent manner across countries, much more so than the reallocation effects, which vary substantially in sign as well as magnitude.

5 Results – Alternative Tariff Reforms

While the foregoing results focused on the elimination or proportional reduction of all tariffs, it is also useful to consider the effect of alternative partial liberalization scenarios to assess how the form of liberalization impacts CO_2 and whether trade policy can realistically be used as a CO_2 mitigation strategy.

5.1 CO_2 Minimizing Trade Liberalization

We start by considering the maximum emissions reductions that could be obtained while engaging in trade liberalization. This is not necessarily a realistic tariff reform objective but will provide some insight into the extent to which it is technically feasible for trade liberalization to reduce emissions. To do this, we search numerically for tariff rate reductions that minimize CO_2 subject to the equilibrium conditions. While it may be possible conduct this search across each tariff rate (country-pair by sector), this process would be computationally intensive and not particularly insightful. Instead, we impose the same percentage reduction in tariffs across broader groups of tariffs. Our main analysis imposes proportional changes in tariffs by sector but we also explore whether allowing the sectoral proportional changes to vary across broad regions (US, other OECD countries, and non-OECD countries) yields markedly different CO_2 reductions.

We find that highly targeted tariff reform can indeed reduce emissions, but the achieved reductions are small. The CO_2 minimizing tariff rate reductions, by sector, are presented in Table A.5 and the emissions and welfare implications of these reductions are presented in Table 5. If the same sectoral tariff rate reductions are imposed across all countries, it is only possible for liberalization to reduce CO_2 by 0.01% (first column of numbers in Figure 5). To do so, the tariff reductions must be heavily concentrated on a few sectors. Tariffs on food production, manufacturing and paper production are eliminated, or nearly so, and tariffs on a few sectors are reduced sharply. These sectors have, on average, relatively low embodied CO_2 (Figure 1).

When tariff reductions are allowed to differ by OECD and non-OECD countries, liberalization can reduce CO_2 levels by 0.21% (second column of numbers in Table 5).

Again, the tariff reductions must be quite concentrated. In OECD countries tariffs on food, manufacturing, textile and wood are eliminated and those on agriculture and electricity are lowered. Tariffs on metal and paper are eliminated in non-OECD countries. Allowing for more heterogeneity in the sector level tariff reductions does not appear to lead to significantly greater CO_2 reductions: if tariff reductions vary separately for the US CO_2 outcomes are not notably affected (last column of results in Table 5).

Our decomposition of the emissions changes illustrates that the reductions in these scenarios are possible because the highly targeted liberalization induces a favorable reallocation from a CO_2 perspective. However, the reductions are limited because they have to overcome the scale and labor-intermediate effects that almost necessarily arise with liberalization.

Although the CO_2 reductions achievable through liberalization are small, it is worth emphasizing that these tariff reductions would also slightly increase real GDP. Due to the bias in the existing tariff structure documented in Figure 1, trade liberalization therefore offers an opportunity for CO_2-negative economic growth. When we allow tariff reductions to vary by sector and OECD designation (second column of results), real income increases by 0.08%, \$54 billion while damages from CO_2 fall by over \$2.9 billion. As we discuss below, stronger results along these lines are possible if some tariffs are allowed to increase, though certain caveats apply in that case. It is important to note, however, that not all regions experience this CO_2-negative growth. Across all counterfactuals, total CO_2 from OECD countries actually rises, while total CO_2 from non-OECD countries falls. In contrast, real income rises across both sets of countries.

5.2 Partial Liberalization Schemes

Given that the extremely concentrated tariff reform obtained from the previous analysis leads to only modest emissions reductions, it is natural to expect that more realistic tariff reductions will generally lead to emissions increases. Even proposals that induce a relatively favorable sectoral reallocation would need to overcome the increase in intermediate input use as well as the scale affect that liberalization would bring about. Nevertheless, potential liberalization schemes vary substantially in terms of how they affect these underlying channels, making it useful to assess the CO_2 implications of broadly realistic schemes.

5.2.1 Proportional versus Fixed Tariff Reductions

To illustrate some of the mechanisms at work, we start by comparing the proportional reduction of all tariffs to a "fixed" tariff reduction, whereby all tariffs are reduced by the same percentage point up to a tariff rate of zero. Table 6 compares proportional reduction to fixed reductions that reduce average tariffs by a roughly 50 and 80%. For the 50% cut in tariffs, fixed reductions are worse from both the point of view of output and emissions: the fixed reductions lead to a smaller increase in output but a bigger increase in CO_2. In terms of output, this reflects the fact that in a proportional reduction, there is a greater reduction in the highest tariffs, something that will generally induce a larger reduction in the deadweight loss from tariffs. In terms of emissions, the decomposition reveals two reasons why the fixed reduction leads to relatively larger emissions increases. First, the labor-intermediate channel is stronger in the fixed reduction case, reflecting the fact that tariffs tend to be relatively low on sectors that are used more frequently as intermediate inputs to begin with and so are reduced by more under the fixed vs. proportional case. Second, while the proportional reduction induces a negative reallocation effect by undoing the the existing bias in the structure of tariffs, the fixed reduction actually has a positive reallocation effect.

For the deeper cut in tariffs, the differences between proportional and fixed reductions decline, but the proportional reductions continue to yield larger output gains and smaller CO_2 increases. The stronger increase in emissions for the proportional reductions occurs because of a strong increase in the labor-intermediate channel, relative to the increase in the scale effect and reduction in the reallocation effect. There is not a similarly strong increase in the labor-intermediate channel for the fixed reduction case. The differences between reduction schemes will become smaller for even deeper cuts, which push all tariffs close to zero in either case.

5.2.2 Alternative Liberalization Schemes

Our results thus far suggest that policies that go further in the direction of reducing the largest tariffs could potentially be even more beneficial. We consider three stylized liberalization strategies along these lines, a "Swiss Formula" approach and schemes that reduce "tariff peaks" and "tariff escalation".[13] The Swiss Formula, which has long been considered as part of multilateral trade liberalization talks, is given as $\tau' = \frac{A \times \tau}{A + \tau}$, where τ is the original tariff rate, τ' is the new tariff rate and A is a parameter that determines the rate of tariff reduction and the maximum possible tariff rate. It implies proportionately greater tariff reductions on initially higher tariffs so that tariffs close to zero will be relatively unchanged, while a hypothetical tariff rate close to infinity would be reduced to the maximum tariff rate, A. It is therefore a scheme that simultaneously harmonizes and reduces tariffs. We apply the Swiss Formula globally (i.e. on all sectors by country-pair tariff rates).

The tariff peaks approach targets reductions at particularly high tariffs, which was a

[13] In practice, these approaches would apply at a much more disaggregated level than our industry classifications allow for in this analysis. In this sense, our analysis is a somewhat general analysis of the effects of underlying policies of this nature rather than an exact attempt to evaluate a particular proposal.

major theme during the Doha Round of WTO negotiations. We implement reductions in tariff peaks by setting all tariffs that exceed a maximum rate to the maximum rate.[14] Although tariff peak reductions are attained through a Swiss Formula approach as well, the tariff peaks approach isolates the reductions to only the highest tariffs.

Tariff escalation refers to a common situation where tariffs increase along processing chains, or that tariffs on upstream sectors tend to be lower than tariffs on downstream sectors. The motivation for reducing tariff escalation is typically to increase market access for processed goods from developing countries. but in terms of CO_2, reducing tariff escalation may work to correct the environmental bias in trade policy (Shapiro 2019). We mimic the reduction of tariff escalation in our aggregate data by creating groups of "upstream" and "downstream" sectors, then setting the maximum tariff rate for downstream sectors to the average tariff rate of upstream sectors multiplied by a scalar.[15]

Global CO_2 and welfare impacts for the Swiss Formula, tariff peaks and tariff escalation liberalizations are presented in Table 7. We present results for the Swiss formula for maximum tariff rates of 0.25 and 0.05 (first two columns of results). At a maximum tariff rate of 0.25, applying the Swiss Formula results in real income gains of nearly 0.4%, which is almost the full real income increase from removing all tariffs. Unlike the tariff removal case, however, this strong increase in real income is combined with a relatively modest, 0.28%, increase in CO_2. Lowering the maximum tariff rate leads to small increases in real income, but much larger, in percentage terms, increases in CO_2. As the maximum tariff rate falls, the Swiss Formula puts more downward pressure on all tariffs, which causes emissions to increase through the scale effect and, especially, through the labor-intermediate effect (compare first two columns of results in Table 7). Increases in these two effects dominate the slightly greater reductions due to the reallocation effects. As a result, the welfare gain per dollar of CO_2 damage is almost twice as large at a maximum tariff rate of 0.25 compared to 0.05.

A similar pattern appears for the tariff peaks case (third and fourth column of results in Table 7). As for the Swiss Formula, we present results for a maximum tariff rate of 0.25 and 0.05. The main difference to the Swiss Formula case is that the real income and CO_2 impacts are smaller. Since reducing the tariff peaks lowers only a subset of tariffs, the real income gains and the increases in CO_2 from the scale and labor-intermediate effects are more

[14]This approach is consistent with the WTO generally recognizing a tariff above 15% as a tariff peak for developed countries, although definitions of tariff peaks often consider a tariff's relative size (e.g. whether it is 3 times a country's average rate).

[15]Specifically, we define sectors as either "upstream" if less than 25% of the sectors' global gross output goes to final consumption or "downstream" if otherwise. The upstream sectors based on this definition are Chem, Coal, Metal, Min, Mine, NGas, Oil, Petrol, Paper, Wood. Then, for each importer we set a maximum tariff rate for downstream sectors as the value weighted mean tariffs on upstream sectors multiplied by a scalar. Any tariff rates in downstream sectors that exceed the maximum are lowered to the maximum.

limited. At a maximum tariff rate of 0.25, the labor-intermediate channel increases CO_2 by a relatively modest 0.18%.

Results for reducing tariff escalation are in final two columns of Table 7. We report results where the maximum upstream tariff is 4 times and 1.5 times the downstream average. In general, we find that the reduction in tariff escalation yields quite large increases in real income 0.33% – or nearly 3/5ths of the real income increase of totally removing tariffs – but does so with very small increases in CO_2, 0.15% for the most severe reduction in escalation. The key difference between tariff escalation and the other liberalization schemes is the much weaker labor-intermediate channel.

5.2.3 Comparison of Liberalization Schemes

To better understand the CO_2 implications of the liberalization scenarios, we can consider the emissions effects of each liberalization scenario when the policy parameters are set so as to ensure the same change in global real income.[16] These results are summarized in Figure 2. The starting and ending points are the same for most of the policies because they always correspond to either no liberalization at all or complete liberalization. Given the nature of our stylized escalation reduction case, however, this scheme is necessarily a partial liberalization scheme and so does not span the entire range of possible real income changes.

We see from the diagram that the fixed tariff reductions clearly generate more emissions than the proportional reductions. The Swiss Formula, tariff peaks reduction and escalation reduction all do better than the proportional reduction. Comparisons between the latter three policies are more mixed and depend on the level of real income change under consideration. In general, however, the escalation reduction seems to be especially notable at delivering output increases while generating low CO_2. This scheme actually *decreases* emissions up to a welfare increase of about 0.25%. It outperforms the other two schemes until we get fairly close to the very limit of the policy as we have defined it. Comparing the Swiss Formula and Tariff Peaks reduction, the Swiss Formula does better up about a 0.20% real income change, beyond which the tariff peaks reductions outperforms. These two policies have fairly similar emissions per real income generated throughout. The emissions level notably shoots up under both the Swiss Formula and tariff peaks approaches beyond a global income increase of about 0.45%. This means that all but the last 0.05% of attainable global income increases can be attained with substantially lower increased emissions. It should be noted, however, that even in this region the dollar value of the output increase is still larger than the additional CO_2 damage at standard externality valuations.

[16] The policy parameters are changes in the tariff rates for the proportional and fixed reductions cases, the maximum tariff rate for the Swiss Formula and tariff peaks cases and the scalar on the average upstream tariff rate for the escalation case.

Table 8 provides decompositions of the effect of these policies at a global real income of 0.25%. Comparing across all five policies, we see that the fixed decrease is associated with a very high labor-intermediate effect and also modest emissions decreases from reallocation. These seem to reflect in part the fact that the average tariff rate change required in order to deliver a 0.25% increase in global real output is relatively large. The proportional reduction does better in part because the same output increase is accomplished through a lower tariff reduction, leading to a significant tempering of the labor-intermediate effect. The Swiss Formula, tariff peaks reduction and escalation reduction all achieve the welfare increase with even more modest tariff rate decreases and in part of this reason, further limit the labor-intermediate effect. Particularly in the case of escalation, these policies are also associated with a more favorable reallocation effect. The differences across liberalization options is not small. Relative to the even the Swiss Formula and tariff peaks reduction – which themselves increase emissions substantially less than fixed or proportional tariff reductions – reducing tariff escalation generates \$1.6-1.8 billion less in CO_2 damages for the same change in real income.

5.3 Mean Preserving Harmonization

We now expand our analysis beyond liberalization to considering reform scenarios with tariff increases as well. These scenarios are better able to reduce emissions through reallocation and the labor-intermediate channels than scenarios that do not increase tariffs. We display results for a uniform within-country harmonization, where the average tariffs in each country are kept roughly constant, in Table 9. The first column of results shows that such a harmonization increases output (0.42%) but reduces CO_2 (0.44%). This is remarkable given that carbon neutral output increases are generally considered a rare possibility, whereas here we see significant carbon-negative output increases. These results are comparable to those in Shapiro (2019). Our decomposition shows that the CO_2 reductions result from favorable reallocation effects combined with a very modest labor-intermediate effect.

To better isolate the channels of adjustment underlying these results, we separately impose the tariff increases and the tariff decreases implied by the mean preserving harmonization (second and third column of results in Table 9). Harmonizing tariffs increases output because the efficiency gains from reducing large tariffs (over \$300 billion) are disproportionately larger than the efficiency losses from increasing small tariffs (\$14.2 billion). In terms of CO_2, the modest labor-intermediate effect is the result of average tariffs remaining constant, so the impact of tariff increases and decreases on the labor-intermediate effect essentially offset each other. The relatively strong reallocation effects occur because the tariff reductions and increases both reduce emissions through reallocation.

Decomposing the harmonization into tariff increases and decreases shows that the CO_2 reductions are dependent on tariff increases. The reductions in above average tariffs alone actually increases emissions, while the tariff increases alone lower emissions by 0.78%. Comparing the monetary value of the CO_2 to the real income changes for the tariff increases and decreases brings into question the "win-win" nature of the mean preserving harmonization results. Notably, the costs of the tariff increases that are essential for a harmonization to reduce emissions is substantially larger than the CO_2 costs at standard valuations. Moreover, global welfare taking into account the CO_2 externality is greatest for the tariff reductions alone ($297 billion relative to $291 billion for the mean preserving harmonization and -$3.2 billion for the tariff increases).

The last column of Table 9 shows the effect of a harmonization that roughly fixes global output rather than fixing the average tariff rate in each country. Since the mean preserving harmonization increases welfare, it is possible to combine harmonization with substantial tariff increases while still keeping global welfare fixed. We can see that in this case, large emissions reductions exceeding 2.7% can be attained. This is again in part due to the labor-intermediate effect, now accounts for a fairly substantial decrease. However, the largest effect by far is the reallocation effect. These results imply that tariffs could be used in principle to attain substantial emissions reductions without reducing global welfare. The caveat discussed in the previous paragraph in the context of mean preserving harmonization, however, applies with even greater strength here: the implicit mitigation costs of these increases greatly exceeds the externality damage.

5.4 Sensitivity Analysis

Each panel in Table 10 reports results under different data and modeling assumptions for our main counterfactuals: tariff removal, Swiss Formula, reduction of tariff peaks and reduction of tariff escalation. The first row in each panel displays results under our central assumptions. The next three rows report results under different assumptions regarding the trade elasticities. Results in the second row are generated using elasticities from Shapiro (2019) and are very similar to our central results, which use elasticities from the GTAP database. In the next two rows we report results after scaling the entire vector of trade elasticities up and down by 50% to explore the impacts of the overall levels of trade elasticities, while maintaining the relative differences across sectors. Raising the trade elasticities leads to a larger emissions across all three counterfactuals, as tariff reforms have stronger scale and labor-intermediate effects, which offset the strong reallocation effect.

Results in the fifth row show that using the full sectoral detail in the GTAP data does not affect our central findings.

6 Results – Other Counterfactuals

Our results to this point have focused on the effects of current tariffs and plausible trade liberalization scenarios on CO_2. However, we expect the labor-intermediate channel that we identify to be an important determinant of emissions changes in many other contexts. In this section, we show that this is true for two natural extensions of our analysis of tariffs: tariffs on embodied emissions and turnover taxes.

6.1 Tariffs on Embodied Emissions

Given the broad trade and environment literature on carbon tariffs, we first assess to what extent the labor-intermediate channel plays a role in the emissions reductions due to climate related trade policy. We do so by imposing a uniform global tariff on the CO_2 embodied in traded goods. This counterfactual is distinct from typical carbon tariff proposals, which would be paired with sub-global climate policy, but should utilize the same channels. The impacts of 25 and 50$/t$CO_2$ tariffs on embodied CO_2 at the industry-origin level are reported in the first two columns of Table 11. Across all three values of these tariffs, the labor-intermediate channel accounts for over a third of the emissions reductions and greatly exceeds the scale effect. While these results certainly point to the general nature of the labor-intermediate channel, it is worth noting that the strong labor-intermediate effect is partially the result of embodied CO_2 being lower for labor intensive, or embodied labor intensive, goods.

Throughout our analysis we have found that trade policy is a costly mitigation option. Our results for tariffs on embodied CO_2 shows that this is true even for trade policy designed for mitigation purposes. A tariff on embodied CO_2 should at least resemble the optimal tariff structure for CO_2 mitigation, but it is still a costly mitigation option. Even if the tariff is set at 50 $/t$CO_2$, and therefore equal to the marginal external cost, the reduction in real income ($82 billion) greatly exceeds the reduced damages from CO_2 ($23 billion). The limited effectiveness of this policy stems from the fact that, even if applied globally, trade policy applies to only a fraction of CO_2 emissions.

6.2 Turnover Taxes

In order to further explore some of the mechanisms underlying our tariff results, we also report the effects of introducing turnover taxes, which are indirect taxes on gross sales that apply at each stage in production. While turnover taxes used to be common across the world, they have largely been replaced by value-added taxes in large part to avoid the cascading effects of taxing intermediate goods. For our purposes, the primary reason to evaluate the effects of this somewhat outdated tax instrument is that it illustrates the effects of a policy that taxes intermediates as tariffs do, but in a way that includes domestic transactions as well. Turnover taxes can also be indirectly informative about other indirect taxes. For example, a sales tax in practice functions as a tax on business inputs to a substantial extent (Phillips and Ibaid 2019). Even a value-added tax, which by construction is meant to avoid taxing inputs, is likely to tax inputs in countries with weak administrative capacity where firms do not always receive the refunds that they are owed (Ebrill et al. 2001; Sharma 2020).

To implement the turnover tax we consider a fixed tax on all gross sales across the world (e.g. adding a fixed value to τ_{ij}^{s}), imposed on top of existing tariffs. Results for increasing values of the turnover tax are shown in the final two columns of Table 11. This policy has a strong impact on global CO_2, reducing emissions by nearly 7.5% for a 3% tax. The labor-intermediate channel accounts for nearly half of the reduction in CO_2, with the reallocation channel making up the other half. The reallocation channel is strong for the turnover tax because coal is heavily taxed – through all the goods in which it is embodied – relative to natural gas. The welfare cost, and scale effect, of this policy is modest relative to the tariff increases we saw in a few different contexts earlier because it applies much more uniformly across sectors and countries. Unlike the trade policies we have studied, the turnover tax can be a welfare improving mitigation option, at least at low levels. At conventional valuations of the external cost of CO_2, the lost real income is less than the CO_2 benefits for turnover taxes of 1% and 3%. However, the turnover tax only crudely targets CO_2 emissions, so it is likely to be considerably less efficient than a carbon tax.

7 Conclusion

We study the CO_2 impact of existing global tariffs as well as several tariff reform scenarios using a quantitative general equilibrium model. We find that removing all existing tariffs increases emissions in substantial part because it increases the output of intermediate goods – including fossil fuels – relative to final output. This is because tariffs are a tax on material but not on labor, and so their removal would reduce the price of intermediates relative to wages.

Owing to this mechanism, complete liberalization leads to emissions increases that exceed the global output increase in percentage terms. This does not mean, however, that tariffs are a reasonable mitigation strategy: the benefits of complete liberalization greatly exceed the global CO_2 cost at standard valuations of the externality. We also consider emission effects under several partial liberalization scenarios and find that approaches entailing the reduction of the highest initial tariffs could increase global output at an especially modest CO_2 cost.

While we uncover the importance of the labor-intermediates channel in this specific context of evaluating the effect of existing tariffs, this mechanism is likely to be important in a wide range of other contexts as well. For example, we demonstrate that this channel would account for a significant fraction of the emissions reductions brought about by hypothetical carbon tariffs. We also verify that policies that tax intermediate goods more generally are likely to reduce emissions in significant part through this channel. Since other forms of indirect taxes are also likely to function as taxes on inputs to some degree in practice, these insights would naturally be applicable in those contexts as well. These are only a few specific examples of course: many global policies and trends are likely to affect the incentives to use intermediates relative to wages, and therefore affect emissions too through this mechanism.

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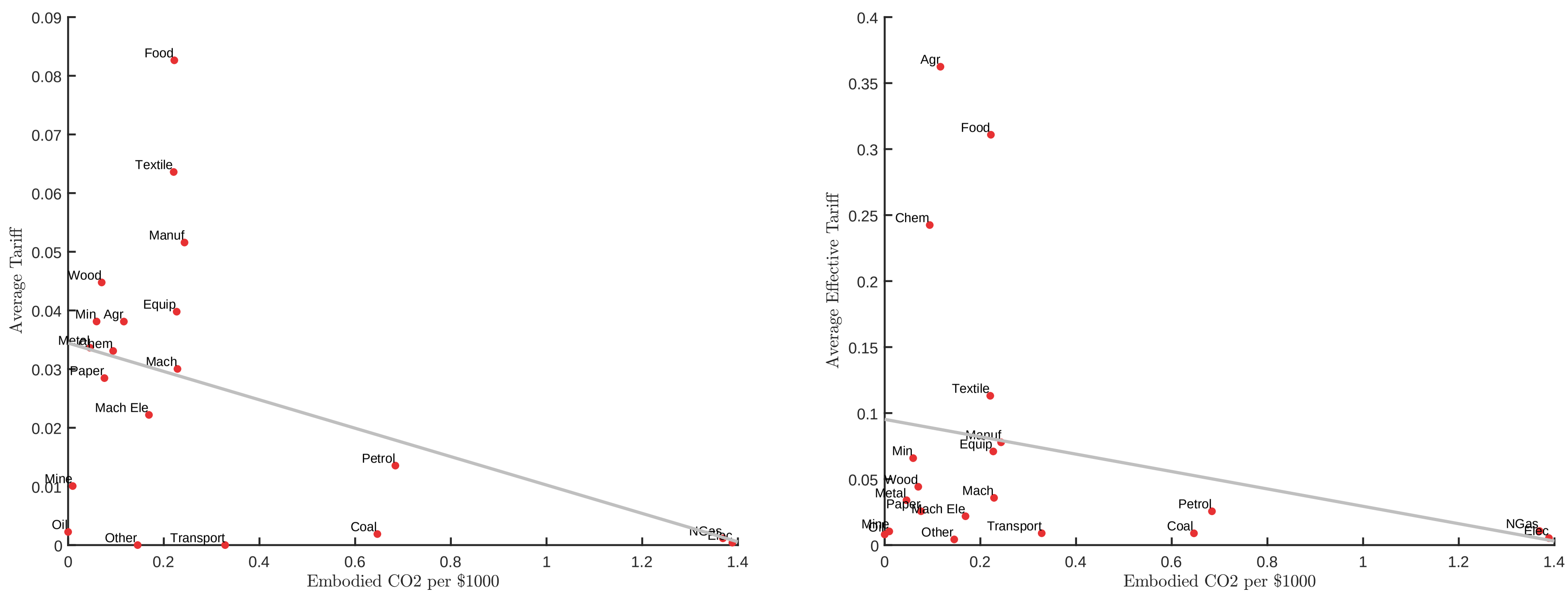
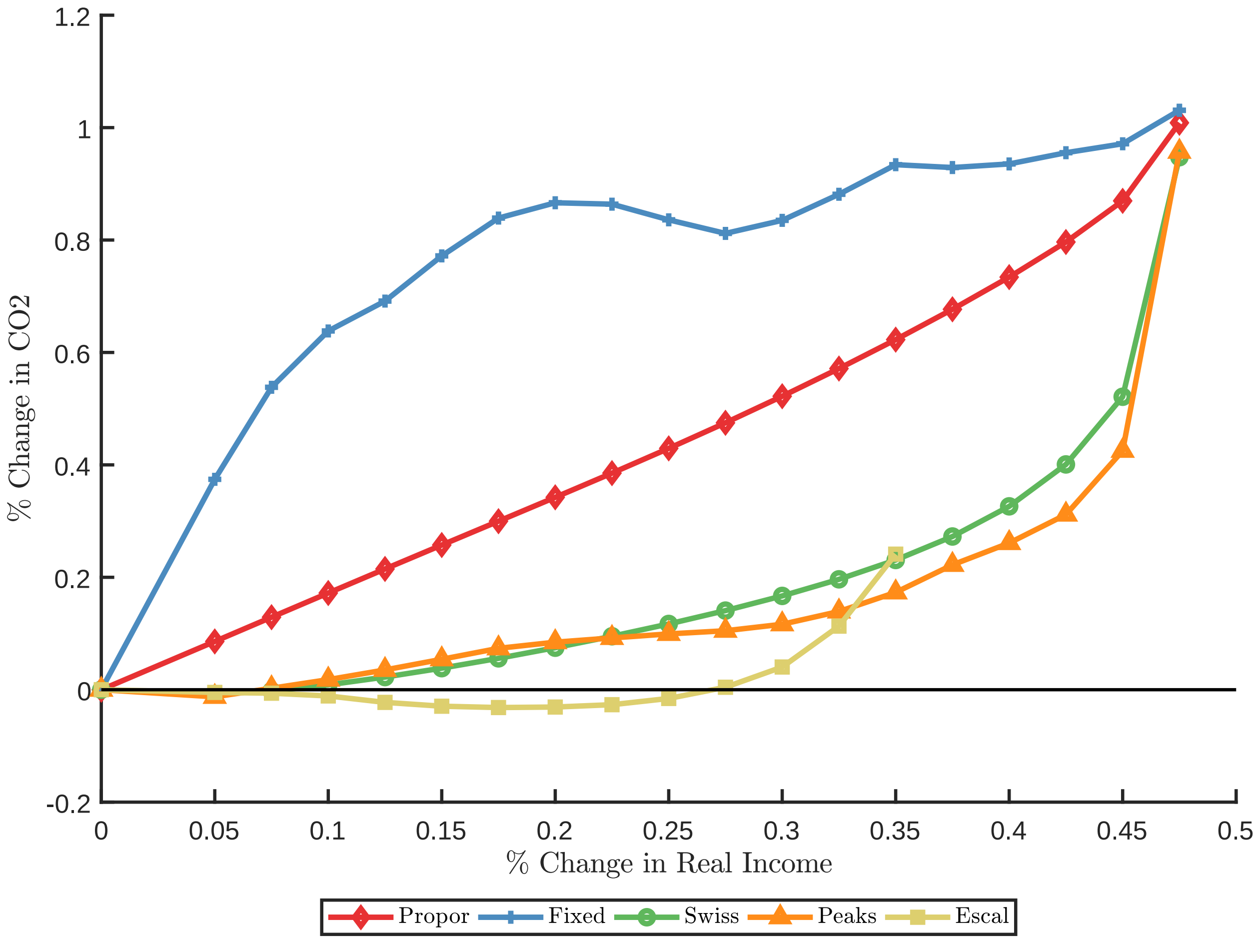


Notes: Average tariff rate is simple average. Effective tariffs are changes in country-sector prices when tariffs are removed, but wages are fixed. Average tariffs are weighted by sector output. To calculate average embodied emissions, embodied emissions for each sector are calculated from baseline final consumption, then divided by sector output.

Figure 1: Average Tariff vs Embodied CO_2



Notes: Real income increases beyond 0.35 are not possible with out stylized scheme to reduce tariff escalation.

Figure 2: Comparison of Liberalization Scenarios

					CO_2 (Mt)		
	ϵ_s	Value (billion $)	% traded	Int. Share	Used	Using	Embodied
Agr	4.87	4803.28	11.69	0.40	0.00	391.07	565.18
Chem	6.60	7133.59	33.83	0.69	0.00	867.23	676.95
Coal	6.10	450.61	31.98	0.42	12007.97	176.85	291.72
Elec	5.60	2508.74	2.22	0.61	0.00	12663.33	3484.84
Equip	6.37	5202.78	34.40	0.74	0.00	62.41	1197.75
Food	5.08	6977.15	13.83	0.71	0.00	281.56	1569.30
Mach	8.10	7082.84	37.51	0.66	0.00	125.87	1633.95
Mach Ele	8.80	3446.16	41.26	0.76	0.00	39.56	584.56
Manuf	7.50	1372.74	24.83	0.62	0.00	57.67	336.58
Metal	7.38	6663.07	23.78	0.71	0.00	1152.57	305.83
Min	5.80	1860.85	10.64	0.64	0.00	1150.45	111.30
Mine	1.80	1136.73	39.54	0.47	0.00	154.10	10.91
NGas	31.48	768.83	39.74	0.32	5938.60	380.58	1054.05
Oil	10.40	2658.31	58.54	0.20	187.28	202.55	0.04
Other	3.80	72200.33	3.43	0.40	0.00	1137.71	10492.77
Petrol	4.20	4431.29	20.59	0.85	10400.67	810.33	3043.00
Paper	5.90	2339.04	13.23	0.62	0.00	185.01	178.14
Textile	7.59	3125.17	29.79	0.70	0.00	87.54	705.01
Transport	3.80	6746.38	11.63	0.65	0.00	4729.33	2214.14
Wood	6.80	1111.28	23.73	0.65	0.00	35.28	78.50

Notes: CO_2 by using sector will not sum to total global CO_2 because it does not capture emissions from goods used by households. Tariff rate column reflects the simple average tariff facing each sector.

Table 1: Summary Statistics by Sector

				CO_2 (Mt)			
	GDP (billion $)	Value (billion $)	Int. Share	Using	Embodied	Emb. tCO_2 per 1000 $	Avg. Tariff
chn	6818.05	20167.27	0.66	6728.58	5795.37	0.29	0.06
usa	15260.89	28308.01	0.46	4150.00	5593.26	0.20	0.05
ind	1779.37	3702.45	0.52	1613.41	1646.41	0.44	0.05
rus	1798.26	3529.94	0.49	1320.23	1323.87	0.38	0.03
jpn	5669.07	11578.14	0.51	902.01	1262.69	0.11	0.05
deu	3333.24	6799.17	0.51	560.28	858.75	0.13	0.04
kor	1055.78	2930.75	0.64	445.72	492.59	0.17	0.05
can	1685.79	3189.38	0.47	418.74	509.78	0.16	0.05
gbr	2246.81	4391.42	0.49	362.55	655.65	0.15	0.05
mex	1134.25	1994.79	0.43	344.69	428.20	0.21	0.03
aus	1319.15	2644.46	0.50	342.96	391.98	0.15	0.05
irn	512.48	887.44	0.42	332.52	463.20	0.52	0.03
idn	834.53	1662.94	0.50	328.51	400.44	0.24	0.05
ita	2046.38	4607.82	0.56	313.57	510.17	0.11	0.05
sau	678.52	1060.90	0.36	300.27	366.81	0.35	0.03
bra	2312.13	4241.54	0.45	296.85	445.41	0.11	0.04
zaf	382.89	908.37	0.58	292.42	239.71	0.26	0.04
fra	2538.97	5311.84	0.52	280.75	522.77	0.10	0.04
pol	462.92	1087.72	0.57	245.54	287.85	0.26	0.04
esp	1365.16	2716.05	0.50	241.66	324.53	0.12	0.04

Notes: The top 20 countries comprise 80% of total CO_2, 78% of total embodied CO_2 and 78% of global GDP. Tariff rate column reflects the simple average tariff set by each country.

Table 2: Emissions by Country

	Proport.	OECD	Non-OECD
Δ E (%)	1.03	0.11	0.91
Scale	0.47	0.18	0.30
Labor-Intermediate	1.07	0.32	0.68
Reallocation	-0.51	-0.40	-0.08
Δ E (mT CO2)	294.1	30.5	259.1
OECD	148.2	28.5	117.3
non-OECD	145.9	2.0	141.8
EV (% of GDP)	0.47	0.18	0.30
EV (billion $)	323.8	125.2	204.1
OECD	178.8	50.4	128.7
non-OECD	145.0	74.8	75.3
CO_2 Damage (billion $)	14.71	1.53	12.95
Δ P (%)	-1.18	-0.40	-0.75
Change in Avg. Tariff Rate	-2.677	-0.274	-2.403

Notes: First column displays results for the elimination of global tariffs. Final two columns report results from individually removing OECD and Non-OECD tariffs.

Table 3: Decomposition of Impacts of Removing Global Tariffs

	chn	usa	ind	rus	jpn	deu	can	kor	irn	gbr
Δ E (%)	0.141	0.026	-0.099	0.088	-0.057	-0.011	0.024	0.073	0.013	-0.006
Scale	0.034	0.009	0.034	0.010	0.020	0.004	0.004	0.103	0.011	0.003
Labor-Intermediate	0.114	0.025	0.017	0.046	0.022	0.009	0.008	0.173	0.010	0.006
Reallocation	-0.008	-0.008	-0.150	0.031	-0.099	-0.024	0.012	-0.203	-0.008	-0.015
Δ E (mT CO2)	40.1	7.4	-28.4	25.0	-16.3	-3.2	6.7	20.9	3.8	-1.7
Domestic	14.0	1.9	-16.4	-22.3	-6.5	-0.5	4.2	15.3	-24.3	-0.3
Other	26.1	5.6	-12.0	47.2	-9.7	-2.7	2.6	5.6	28.1	-1.5
EV (% of GDP)	0.034	0.009	0.034	0.010	0.020	0.004	0.004	0.103	0.011	0.003
EV (billion $)	23.3	5.9	23.4	7.0	13.3	3.0	2.4	70.4	7.8	2.0
Domestic	-30.3	-9.1	-0.9	-6.5	-1.1	-2.6	-1.2	32.9	1.4	-1.2
Other	53.7	15.0	24.3	13.6	14.4	5.6	3.6	37.4	6.4	3.2

(a) Top 10 Countries by Baseline Emissions

	mex	ita	idn	aus	bra	fra	sau	zaf	pol	tur
Δ E (%)	0.017	-0.006	0.041	0.071	0.053	-0.006	0.038	0.048	-0.001	-0.020
Scale	0.004	0.002	0.002	0.003	0.011	0.002	0.002	0.005	0.000	0.009
Labor-Intermediate	0.007	0.005	0.008	0.016	0.036	0.007	0.015	0.006	0.001	0.006
Reallocation	0.006	-0.013	0.031	0.052	0.006	-0.015	0.021	0.037	-0.003	-0.035
Δ E (mT CO2)	4.7	-1.7	11.8	20.2	15.1	-1.6	10.8	13.7	-0.3	-5.6
Domestic	0.7	-0.3	0.4	2.2	1.0	0.0	-4.1	9.2	-0.1	-2.9
Other	4.0	-1.4	11.4	18.0	14.1	-1.6	14.9	4.4	-0.2	-2.7
EV (% of GDP)	0.004	0.002	0.002	0.003	0.011	0.002	0.002	0.005	0.000	0.009
EV (billion $)	2.4	1.6	1.3	1.9	7.4	1.3	1.4	3.4	0.3	6.1
Domestic	-1.1	-1.2	-1.9	-1.9	-8.1	-1.7	-1.0	-1.0	-0.3	1.1
Other	3.5	2.7	3.1	3.8	15.5	3.0	2.3	4.4	0.6	5.0

(b) Countries 11-20 by Baseline Emissions

Notes: Columns in each panel report counterfactual where individual country's tariffs are set to zero. Tariffs in all other countries remain at baseline levels. "Domestic" rows report changes in CO_2 or EV for country lowering tariffs. "Other" rows report changes for the remaining countries.

Table 4: Impacts of Unilateral Tariff Removal

	Sector	Sector-OECD	Sector-OECD-US
Δ E (%)	-0.01	-0.21	-0.21
Scale	0.03	0.08	0.08
Labor-Intermediate	0.04	0.13	0.13
Reallocation	-0.08	-0.42	-0.42
Δ E (mT CO2)	-3.9	-58.9	-59.0
OECD	13.1	17.6	18.0
non-OECD	-16.9	-76.5	-77.1
EV (% of GDP)	0.03	0.08	0.08
EV (billion \$)	19.5	54.6	54.7
OECD	6.0	20.2	20.2
non-OECD	13.5	34.5	34.5
CO_2 Damage (billion \$)	-0.19	-2.94	-2.95
Δ P (%)	-0.08	-0.24	-0.25
Change in Avg. Tariff Rate	-0.485	-0.582	-0.584

Notes: Columns report impacts of CO_2 reducing tariff reductions at the sector level at the global scale, for OECD and Non-OECD countries separately, and for the US, other OECD countries and Non-OECD countries separately.

Table 5: Decomposition of Impacts of CO_2 Minimizing Tariff Reform

	Proport. (50)	Proport. (80)	Fixed (0.045)	Fixed (0.12)
Δ E (%)	0.37	0.68	0.57	0.74
Scale	0.22	0.38	0.08	0.14
Labor-Intermediate	0.25	0.51	0.35	0.56
Reallocation	-0.09	-0.21	0.14	0.04
Δ E (mT CO2)	107.0	193.6	162.2	211.2
OECD	66.9	114.0	75.1	121.6
non-OECD	40.0	79.6	87.1	89.5
EV (% of GDP)	0.22	0.38	0.08	0.14
EV (billion \$)	149.3	256.2	55.1	96.4
OECD	87.1	147.6	43.5	82.2
non-OECD	62.2	108.6	11.6	14.2
CO_2 Damage (billion \$)	5.35	9.68	8.11	10.56
Δ P (%)	-0.42	-0.78	-0.38	-0.66
Change in Avg. Tariff Rate	-1.338	-2.141	-1.071	-1.964

Notes: "Proportional" columns report results from reducing all tariffs by 50% and 80%. "Fixed" columns report results from reducing all tariffs by same fixed amount. The fixed amount, reported in column headers, is chosen so the average tariff rate weighted by baseline trade flows falls by 50% and 80%, respectively.

Table 6: Decomposition of Impacts of Global Tariff Reductions

	Swiss (0.25)	Swiss (0.05)	Peaks (0.25)	Peaks (0.05)	Escalation (4)	Escalation (1.5)
Δ E (%)	0.28	0.58	0.11	0.34	0.01	0.15
Scale	0.38	0.46	0.29	0.43	0.28	0.33
Labor-Intermediate	0.31	0.67	0.18	0.52	0.18	0.32
Reallocation	-0.41	-0.55	-0.35	-0.61	-0.45	-0.50
Δ E (mT CO2)	78.6	165.4	31.2	98.2	2.9	42.7
OECD	38.3	89.1	2.3	59.4	11.8	35.2
non-OECD	40.4	76.3	28.9	38.8	-8.9	7.5
EV (% of GDP)	0.38	0.46	0.29	0.44	0.28	0.34
EV (billion $)	256.7	312.0	195.7	296.7	191.2	228.4
OECD	110.1	153.4	72.1	135.2	84.9	109.5
non-OECD	146.6	158.7	123.5	161.5	106.2	118.9
CO_2 Damage (billion $)	3.93	8.27	1.56	4.91	0.15	2.13
Δ P (%)	-0.47	-0.83	-0.26	-0.68	-0.39	-0.58
Change in Avg. Tariff Rate	-1.022	-1.903	-0.232	-1.508	-0.462	-0.868

Notes: The value in the parenthesis of column headings is maximum tariff rate for Swiss formula and Tariff Peaks cases and the scalar on downstream emissions for the Escalation cases.

Table 7: Decomposition of Impacts of Liberalization Scenarios

	Proport.	Fixed	Swiss	Peaks	Escalation
Δ E (%)	0.43	0.84	0.12	0.10	-0.02
Scale	0.25	0.25	0.25	0.25	0.25
Labor-Intermediate	0.29	0.67	0.09	0.14	0.14
Reallocation	-0.11	-0.09	-0.22	-0.29	-0.40
Δ E (mT CO2)	122.5	238.5	33.4	28.3	-4.4
OECD	76.1	140.1	13.3	1.5	8.1
non-OECD	46.4	98.5	20.0	26.8	-12.6
EV (% of GDP)	0.25	0.25	0.25	0.25	0.25
EV (billion $)	170.4	170.4	170.4	170.4	170.4
OECD	99.1	127.6	67.3	61.8	79.3
non-OECD	71.3	42.8	103.1	108.6	91.1
CO_2 Damage (billion $)	6.13	11.93	1.67	1.42	-0.22
Δ $\bar{P}$ (%)	-0.48	-0.90	-0.22	-0.21	-0.32
Change in Avg. Tariff Rate	-1.504	-2.590	-0.461	-0.145	-0.344

(a) Change in Real Income = 0.25%

	Proport.	Fixed	Swiss	Peaks	Escalation
Δ E (%)	0.62	0.93	0.23	0.17	0.24
Scale	0.35	0.35	0.35	0.35	0.35
Labor-Intermediate	0.46	0.82	0.25	0.27	0.40
Reallocation	-0.18	-0.24	-0.37	-0.44	-0.51
Δ E (mT CO2)	177.7	266.5	65.9	49.4	68.8
OECD	106.2	155.0	30.6	13.6	53.1
non-OECD	71.5	111.5	35.3	35.8	15.7
EV (% of GDP)	0.35	0.35	0.35	0.35	0.35
EV (billion $)	238.6	238.6	238.6	238.6	238.6
OECD	137.9	167.9	100.1	92.8	124.0
non-OECD	100.7	70.7	138.5	145.8	114.6
CO_2 Damage (billion $)	8.89	13.33	3.29	2.47	3.44
Δ $\bar{P}$ (%)	-0.72	-1.04	-0.40	-0.38	-0.67
Change in Avg. Tariff Rate	-2.015	-2.651	-0.861	-0.585	-1.104

(b) Change in Real Income = 0.35%

Notes: Columns reflect each liberalization scenario when policy is set to achieve a target change in real income.

Table 8: Comparing Liberalization Scenarios at Target Real Income

	Harmonization	Reduction Only	Increase Only	Fixed Real Inc
Δ E (%)	-0.44	0.34	-0.78	-2.72
Scale	0.42	0.44	-0.02	0.00
Labor-Intermediate	0.23	0.55	-0.31	-0.94
Reallocation	-1.08	-0.65	-0.44	-1.81
Δ E (mT CO2)	-124.6	97.7	-221.3	-775.4
OECD	-34.6	52.6	-89.2	-365.8
non-OECD	-90.0	45.1	-132.1	-409.5
EV (% of GDP)	0.42	0.44	-0.02	0.00
EV (billion $)	285.2	301.5	-14.3	0.0
OECD	120.5	123.7	-5.1	-30.3
non-OECD	164.6	177.9	-9.2	30.3
CO_2 Damage (billion $)	-6.23	4.89	-11.07	-38.77
Δ P (%)	-0.39	-0.73	0.35	1.07
Change in Avg. Tariff Rate	1.474	-1.433	2.907	11.063

Notes: Tariff rates harmonized by importing country so that average tariff rate within each country is constant. Final column scales harmonized tariff rates so that real income is unchanged.

Table 9: Decomposition of Impacts Mean Preserving Harmonization

	ΔE (%)	Scale	Labor-Int	Realloc
Central	1.03	0.47	1.07	-0.51
ϵ^s - Shapiro (2019)	0.96	0.47	1.01	-0.51
$\epsilon^s * 1.5$	1.77	0.92	2.13	-1.27
$\epsilon^s * 0.66$	0.89	0.27	0.81	-0.20
GTAP Sectors	0.96	0.54	1.17	-0.74

(a) Tariff Removal

	ΔE (%)	Scale	Labor-Int	Realloc
Central	0.28	0.38	0.31	-0.41
ϵ^s - Shapiro (2019)	0.22	0.37	0.26	-0.41
$\epsilon^s * 1.5$	0.67	0.72	0.67	-0.72
$\epsilon^s * 0.66$	0.18	0.22	0.22	-0.26
GTAP Sectors	0.21	0.44	0.36	-0.60

(b) Swiss Formula (0.25)

	ΔE (%)	Scale	Labor-Int	Realloc
Central	0.11	0.29	0.18	-0.35
ϵ^s - Shapiro (2019)	0.05	0.29	0.12	-0.35
$\epsilon^s * 1.5$	0.50	0.56	0.51	-0.57
$\epsilon^s * 0.66$	-0.01	0.16	0.09	-0.26
GTAP Sectors	0.03	0.36	0.23	-0.56

(c) Tariff Peaks (0.25)

	ΔE (%)	Scale	Labor-Int	Realloc
Central	0.04	0.30	0.22	-0.48
ϵ^s - Shapiro (2019)	0.04	0.34	0.29	-0.59
$\epsilon^s * 1.5$	0.30	0.61	0.50	-0.81
$\epsilon^s * 0.66$	-0.03	0.16	0.17	-0.36
GTAP Sectors	-0.07	0.33	0.17	-0.57

(d) Escalation (3)

Notes: Panel (a) all tariffs removed; Panel (b) Swiss Formula with maximum tariff rate of 0.25; Panel (c) maximum tariff rate of 0.25; Panel (d) maximum upstream tariff is 3 times downstream mean.

Table 10: Main Results Using Alternative Data and Assumptions

	Embodied CO2 (25)	Embodied CO2 (50)	Turnover (0.01)	Turnover (0.03)
Δ E (%)	-0.95	-1.62	-2.59	-7.41
Scale	-0.05	-0.12	-0.03	-0.15
Labor-Intermediate	-0.32	-0.59	-1.34	-3.86
Reallocation	-0.58	-0.92	-1.26	-3.68
Δ E (mT CO2)	-271.5	-460.9	-738.8	-2115.0
OECD	-75.8	-137.9	-270.4	-779.4
non-OECD	-195.7	-323.0	-468.3	-1335.6
EV (% of GDP)	-0.05	-0.12	-0.03	-0.15
EV (billion \$)	-35.2	-81.9	-17.7	-105.2
OECD	15.2	19.4	-8.4	-54.5
non-OECD	-50.3	-101.3	-9.3	-50.6
CO_2 Damage (billion \$)	-13.58	-23.05	-36.94	-105.75
Δ P (%)	0.33	0.63	2.11	6.38
Change in Avg. Tariff Rate	2.236	4.471	1.000	3.000

Notes: Carbon tariffs imposed on industry by origin embodied emissions. Baseline includes pre-existing non-carbon tariffs. Column headers are value of carbon tariff in \$/tCO_2. Turnover tax is implemented by adding a fixed value to all τ_{ij}^s, including those where $i = j$ to existing tariffs. Column labels report the fixed values used.

Table 11: Decomposition of Impacts of Other Policies

Appendix

A Additional Data and Calculations

A.1 Model solution algorithm

The solution algorithm we use to solve the model is adapted from Shapiro (2016). First, we guess a vector of proportional wage changes, $\hat{w}_i$. Next, we use a contraction mapping on (8) and (9) to determine the proportional price changes. We then solve for the values of $\hat{X}_j^t$ and $\hat{X}_j$ and thereby the values of $\hat{X}_{ij}^s$. To do so, we setup (10) and (11) as a linear system in the $\hat{X}_j^t$ values that can be solved using matrix algebra, a process outlined below. Next, we use the calculated $\hat{X}_{ij}^s$ values together with the baseline values from the data to calculate the counterfactual X_{ij}^s values, and check whether the equilibrium condition (7) holds. If it does not hold, then we guess a new vector of proportional wage changes and repeat the process until it does.

We setup the linear system to solve for $\hat{X}_j^t$ by substituting (11) into (10) then summing (10) over destinations, which yields:[17]

$$\begin{bmatrix} \hat{X}_1^1 \\ \hat{X}_1^2 \\ \vdots \\ \hat{X}_2^1 \\ \hat{X}_2^2 \\ \vdots \end{bmatrix} = \begin{bmatrix} \Theta_1^1 \\ \Theta_1^2 \\ \vdots \\ \Theta_2^1 \\ \Theta_2^2 \\ \vdots \end{bmatrix} + \begin{bmatrix} \Omega_{11}^{11} & \Omega_{11}^{12} & ... & \Omega_{12}^{11} & \Omega_{12}^{12} \\ \Omega_{21}^{11} & \Omega_{21}^{12} & ... & \Omega_{22}^{11} & \Omega_{22}^{12} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \Omega_{11}^{21} & \Omega_{11}^{22} & ... & \Omega_{12}^{21} & \Omega_{12}^{22} \\ \Omega_{21}^{21} & \Omega_{21}^{22} & ... & \Omega_{22}^{21} & \Omega_{22}^{22} \\ \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix} \begin{bmatrix} \hat{X}_1^1 \\ \hat{X}_1^2 \\ \vdots \\ \hat{X}_2^1 \\ \hat{X}_2^2 \\ \vdots \end{bmatrix} \tag{A.1}$$

The constants and coefficients are given by:

$$\Theta_i^s = \sum_j \frac{X_{ij}^{sC}}{X_i^s} \left(\frac{\hat{p}_{ij}^s}{\hat{P}_j^s} \right)^{1-\epsilon^s} \hat{T}_{ij}^s \psi_j \left(\phi_j^w \hat{w}_j + \phi_j^D \right)$$

$$\begin{aligned} \Omega_{ik}^{sr} = & \frac{X_{ik}^{sr} / \left(1 + \tau_{ik}^s\right)}{X_i^s} \left(\frac{\hat{p}_{ik}^s}{\hat{P}_k^s} \right)^{1-\epsilon^s} \hat{T}_{ik}^s \\ & + \left(\frac{\hat{p}_{ik}^s}{\hat{P}_k^s} \right)^{1-\epsilon^s} \hat{T}_{ik}^s \frac{X_{ik}^{sC} / \left(1 + \tau_{ik}^s\right)}{X_i^s} \psi_k \left[\sum_u \sum_m \phi_{mj}^u t_{mj}^{\prime u} \lambda_{mj}^{ur} \left(\frac{\hat{p}_{mj}^u}{\hat{P}_j^u} \right)^{1-\epsilon^u} \right] \end{aligned}$$

where $\psi_j = \left[1 - \sum_s \sum_m \phi_{mj}^s t_{mj}^{\prime s} \frac{X_{mj}^{sC}}{X_{mj}^s} \left(\frac{\hat{p}_{mj}^s}{\hat{P}_j^s} \right)^{1-\epsilon^s} \right]^{-1}$. Re-writing the matrix equation in

[17]When summing over destinations we divide X_{ij}^s by $1 + \tau_{ij}^s$ to account for sellers receiving than what buyers pay.

simpler notation $\hat{\boldsymbol{X}} = \boldsymbol{\Theta} + \boldsymbol{\Omega}\hat{\boldsymbol{X}}$, the vector of $\hat{X}_j^s$ can be solved for as follows:

$$\hat{\boldsymbol{X}} = [\boldsymbol{I_{NS}} - \boldsymbol{\Omega}]^{-1} \boldsymbol{\Theta}$$

A.2 EHA Decomposition

To obtain the decomposition in proportional changes, we do the following:

$$E = Q \times \left(\sum_j \sum_s \sum_t \kappa_j^{st} \frac{Q_j^{st}}{Q} \right)$$

$$\hat{E} = \hat{Q} \times \left(\sum_j \sum_s \sum_t \frac{E_j^{st}}{E} \frac{\hat{Q}_j^{st}}{\hat{Q}} \right)$$

$$\hat{E} = \hat{V} \times \frac{\hat{Q}}{\hat{V}} \times \left(\sum_j \sum_s \sum_t \frac{E_j^{st}}{E} \frac{\hat{Q}_j^{st}}{\hat{Q}} \right)$$

Taking the log to interpret in terms of log point changes:

$$log\left(\hat{E}\right) = log\left(\hat{V}\right) + log\left(\frac{\hat{Q}}{\hat{V}}\right) + log\left(\sum_j \sum_s \sum_t \frac{E_j^{st}}{E} \frac{\hat{Q}_j^{st}}{\hat{Q}} \right)$$

A.3 Embodied Emissions

A sector's contribution to emissions is broader than just the direct emissions from the fossil fuels it uses because the intermediate inputs used in production, and the inputs to those inputs, also generate emissions. As a means to compare emissions intensities across sectors, we calculate the emissions "embodied" in a final good, which accounts for direct emissions in production plus the emissions from the inputs use in production, and the inputs used in those inputs, etc.

We calculate embodied emissions at the country-sector level based on the model's accounting identities. In this calculation we treat the consumption of a good in a country as any other sector (i.e. there is a sector that "produces" a consumption composite). We let g index the joint set of production and consumption sectors (which will have $2 * N$ elements). The emissions embodied in the production and consumption, $\tilde{\kappa}_i^g$, are determined by the following relationship:

$$X_i^g \tilde{\kappa}_i^g = E_i^g + \sum_h \sum_f X_{hi}^{fg} \tilde{\kappa}_h^f \tag{A.2}$$

where f indexes the joint set of production and consumption sectors and h indexes countries, X_i^g is the total value of output and E_i^g is total direct emissions for each country-sector pair, and X_{hi}^{fg} is the multi-region input-output matrix. The input-output matrix reflects the total value of output from each country-sector (including all consumption sectors) that is used in each other country-sector. Note that $X_{ij}^{fg} = \theta_{ij}^f X_j^{fg}$ where θ_{ij}^f is the share of expenditure on good f in country j that is from country i. It is straightforward to write (A.2) in matrix form and solve for $\tilde{\kappa}_i^g$.

A.4 Environmental Bias in Tariffs

We use descriptive regressions to explore the correlation between tariff rates and embodied emissions at the importer-industry level, which is the level of analysis in Shapiro (2019), although he uses a more disaggregated database for this exercise. Specifically, we regress importer-industry average tariff rates on importer-industry average embodied CO_2 per dollar. These averages are weighted by the value of trade flows. Results of this analysis are reported in Table A.3. The simple regression (1), implies that a 1 ton increase in CO_2 per dollar is associated with a 5 dollar reduction in tariffs collected. Since this coefficient is negative it can be interpreted as the subsidy for CO_2 intensive goods. This correlation is mostly driven by within importer variation. When we include importer fixed effects, the coefficient remains negative and significant (2). In this case, a one ton increase in embodied emissions is associated with a \$6 reduction in tariff rates. However, the coefficient becomes positive when we include sector fixed effects, suggesting it is variation within sectors driving the bias. It is worth noting that the estimated environmental bias we observe in our aggregated data (6 \$/t) is substantially lower than Shapiro (2019) estimates with much more disaggregated data (40 \$/t).[18] The environmental bias in Shapiro's quantitative analysis will also be stronger because he accounts for non-tariff barriers in addition to tariffs.

[18]Shapiro (2019) presents a range of estimates. The estimate of a 40 \$/t subsidy is the OLS estimate for tariffs only.

	GTAP Sectors
Agr	Paddy rice; Wheat; Cereal grains nec; Vegetables, fruit, nuts; Oil seeds; Sugar cane, sugar beet; Plant-based fibers; Crops nec; Cattle,sheep,goats,horses; Animal products nec; Raw milk; Wool, silk-worm cocoons; Forestry; Fishing
Chem	Chemical,rubber,plastic prods
Coal	Coal
Elec	Electricity
Equip	Motor vehicles and parts; Transport equipment nec
Food	Meat: cattle,sheep,goats,horse; Meat products nec; Vegetable oils and fats; Dairy products; Processed rice; Sugar; Food products nec; Beverages and tobacco products
Mach	Machinery and equipment nec
Mach_Ele	Electronic equipment
Manuf	Manufactures nec
Metal	Ferrous metals; Metals nec; Metal products
Min	Mineral products nec
Mine	Minerals nec
NGas	Gas; Gas manufacture, distribution
Oil	Oil
Other	Water; Construction; Trade; Communication; Financial services nec; Insurance; Business services nec; Recreation and other services; PubAdmin/Defence/Health/Educat; Dwellings
Paper	Paper products, publishing
Petrol	Petroleum, coal products
Textile	Textiles; Wearing apparel; Leather products
Transport	Transport nec; Sea transport; Air transport
Wood	Wood products

Table A.1: Sector Aggregation

ALB-Albania **ARE**-United Arab Emirates **ARG**-Argentina **ARM**-Armenia **AUT**-Austria **AZE**-Azerbaijan **BEL**-Belgium **BGD**-Bangladesh **BGR**-Bulgaria **BHR**-Bahrain **BLR**-Belarus **BOL**-Bolivia **BRA**-Brazil **BWA**-Botswana **CAN**-Canada **CHE**-Switzerland **CHL**-Chile **CHN**-China **CIV**-Cote d'Ivoire **CMR**-Cameroon **COL**-Colombia **CRI**-Costa Rica **CYP**-Cyprus **CZE**-Czech Republic **DEU**-Germany **DNK**-Denmark **ECU**-Ecuador **EGY**-Egypt **ESP**-Spain **EST**-Estonia **ETH**-Ethiopia **FIN**-Finland **FRA**-France **GBR**-United Kingdom **GEO**-Georgia **GHA**-Ghana **GRC**-Greece **GTM**-Guatemala **HKG**-Hong Kong **HND**-Honduras **HRV**-Croatia **HUN**-Hungary **IDN**-Indonesia **IND**-India **IRL**-Ireland **IRN**-Iran Islamic Republic of **ISR**-Israel **ITA**-Italy **JPN**-Japan **KAZ**-Kazakhstan **KEN**-Kenya **KGZ**-Kyrgyztan **KHM**-Cambodia **KOR**-Korea **KWT**-Kuwait **LAO**-Lao People's Democratic Republ **LKA**-Sri Lanka **LTU**-Lithuania **LUX**-Luxembourg **LVA**-Latvia **MAR**-Morocco **MDG**-Madagascar **MEX**-Mexico **MLT**-Malta **MNG**-Mongolia **MOZ**-Mozambique **MUS**-Mauritius **MWI**-Malawi **MYS**-Malaysia **NAM**-Namibia **NGA**-Nigeria **NIC**-Nicaragua **NLD**-Netherlands **NOR**-Norway **NPL**-Nepal **NZL**-New Zealand **OMN**-Oman **PAK**-Pakistan **PAN**-Panama **PER**-Peru **PHL**-Philippines **POL**-Poland **PRT**-Portugal **PRY**-Paraguay **QAT**-Qatar **ROU**-Romania **RUS**-Russian Federation **SAU**-Saudi Arabia **SEN**-Senegal **SGP**-Singapore **SLV**-El Salvador **SVK**-Slovakia **SVN**-Slovenia **SWE**-Sweden **THA**-Thailand **TUN**-Tunisia **TUR**-Turkey **TWN**-Taiwan **TZA**-Tanzania **UGA**-Uganda **UKR**-Ukraine **URY**-Uruguay **USA**-United States of America **VEN**-Venezuela **VNM**-Viet Nam **XAC**-South Central Africa **XCA**-Rest of Central America **XCAR**-Dominican Republic; Jamaica; Puerto Rico; Trinidad and Tobago; Caribbean **XCF**-Central Africa **XEA**-Rest of East Asia **XEAF**-Rwanda; Rest of Eastern Africa **XEE**-Rest of Eastern Europe **XEF**-Rest of EFTA **XER**-Rest of Europe **XNA**-Rest of North America **XNF**-Rest of North Africa **XOC**-Rest of Oceania **XSA**-Rest of South Asia **XSC**-Rest of South African Customs **XSEAS**-Brunei Darassalam; Rest of Southeast Asia **XSM**-Rest of South America **XSU**-Rest of Former Soviet Union **XTW**-Rest of the World **XWAF**-Benin; Burkina Faso; Guinea; Togo; Rest of Western Africa **XWAS**-Jordhan; Rest of Western Asia **ZAF**-South Africa **ZMB**-Zambia **ZWE**-Zimbabwe

Table A.2: Regional Aggregation

	(1)	(2)	(3)
Embodied CO2	-5.01	-6.39	3.89
	(1.48)	(1.39)	(2.01)
R^2	0.0044	0.2	0.15
Obs	2580	2580	2580
FE		Importer	Sector

Notes: Regressions of value-weighted average tariff rate on average embodied emissions by importer-sector. Robust standard errors in parentheses.

Table A.3: Association Between Tariff Rates and Embodied Carbon

		Log			Differential			Copeland + Taylor		
	ΔE (%)	Scale	L-Int	Realloc	Scale	L-Int	Realloc	Scale	Comp	Tech
Proport. (50)	0.37	0.22	0.25	-0.09	0.22	0.25	-0.09	0.22	-0.13	0.30
Proport. (100)	1.03	0.47	1.07	-0.51	0.47	1.07	-0.51	0.47	0.15	0.55
Proport. (1.0025)	0.43	0.25	0.29	-0.11	0.25	0.29	-0.11	0.25	-0.14	0.34
Fixed (1.0025)	0.84	0.25	0.67	-0.09	0.25	0.68	-0.09	0.25	-0.10	0.79
Swiss (1.0025)	0.12	0.25	0.09	-0.22	0.25	0.09	-0.22	0.25	0.01	-0.14
Peaks (1.0025)	0.10	0.25	0.14	-0.29	0.25	0.14	-0.29	0.25	0.09	-0.22
Escalation (1.0025)	-0.02	0.25	0.14	-0.40	0.25	0.14	-0.40	0.25	0.15	-0.41
Embodied CO2 (50)	-1.62	-0.12	-0.59	-0.92	-0.12	-0.59	-0.91	-0.12	0.00	-1.20
Turnover (0.03)	-7.41	-0.15	-3.86	-3.68	-0.15	-3.79	-3.62	-0.15	3.52	-9.81

Notes: The first two rows report proportional reductions in all tariffs of 50 and 100%. The next five rows report results for each liberalization scheme with a change in global real income of 0.25%. The final two rows report results for tariffs on embodied emissions of 50 $/tCO2 and a turnover tax of 0.03.

Table A.4: Alternative Decompositions

	OECD	nonOECD	USA
Agr	0.00	0.00	0.00
Chem	0.00	0.00	0.00
Coal	0.00	0.00	-
Elec	0.00	0.00	-
Equip	0.00	0.00	0.00
Food	0.00	0.00	0.00
Mach	0.00	0.00	0.00
Mach Ele	0.00	0.00	0.00
Manuf	0.80	0.80	0.80
Metal	0.20	0.20	0.20
Min	0.00	0.00	0.00
Mine	0.00	0.00	0.00
NGas	0.46	0.46	-
Oil	0.00	0.00	0.00
Petrol	0.00	0.00	0.00
Paper	0.82	0.82	0.82
Textile	0.40	0.40	0.40
Wood	0.00	0.00	0.00

(a) Sector

	OECD	nonOECD	USA
Agr	0.09	0.00	0.09
Chem	0.00	0.00	0.00
Coal	0.00	0.00	-
Elec	0.46	0.00	-
Equip	0.00	0.00	0.00
Food	1.00	0.00	1.00
Mach	0.00	0.00	0.00
Mach Ele	1.00	0.00	1.00
Manuf	1.00	0.55	1.00
Metal	0.00	0.91	0.00
Min	0.00	0.00	0.00
Mine	0.45	0.00	0.45
NGas	0.00	0.71	-
Oil	0.00	0.00	0.00
Petrol	0.00	0.00	0.00
Paper	0.00	1.00	0.00
Textile	1.00	0.00	1.00
Wood	1.00	0.00	1.00

(b) Sector, OECD

	OECD	nonOECD	USA
Agr	0.09	0.00	0.96
Chem	0.00	0.00	0.00
Coal	0.00	0.00	-
Elec	0.31	0.00	-
Equip	0.00	0.00	0.00
Food	1.00	0.00	1.00
Mach	0.00	0.00	0.00
Mach Ele	1.00	0.00	0.15
Manuf	1.00	0.55	1.00
Metal	0.00	0.92	0.00
Min	0.00	0.00	0.00
Mine	0.27	0.00	0.31
NGas	0.00	0.69	-
Oil	0.00	0.00	1.00
Petrol	0.00	0.00	0.00
Paper	0.00	1.00	0.31
Textile	1.00	0.00	1.00
Wood	1.00	0.00	1.00

(c) Sector, OECD-US

Notes: Values reflect proportion reduction in tariffs. Missing values represent sectors where pre-existing tariffs are zero.

Table A.5: CO_2 Minimizing Tariff Reductions