Trade Barriers and CO_2

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Abstract

We highlight the key role of changes in the transportation and use of intermediate inputs in determining the CO_2 consequences of reductions in trade barriers such as tariffs and transportation efficiency improvements. Reductions in trade barriers increase gross flows relative to value added – a lengthening of value chains – thereby increasing transportation emissions. Reductions in trade barriers also increase wages relative to the price of other goods, which increases the quantity of intermediates relative to labor used in production and, therefore, emissions per value added. Liberalization schemes that temper these channels could achieve substantial output increases with modest increases in CO_2.

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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 understanding how policies unrelated to GHG mitigation can affect GHG levels 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, and how, non-carbon policies work for or against mitigation efforts. Given that natural and man-made trade barriers alter relative prices and therefore the production, composition and movement of goods – especially in the context of pervasive global value chains – and the long literature on the environmental impacts of trade liberalization (see Copeland and Taylor (2004)) it is surprising that the effects of changes in trade policy on GHG emissions have remained relatively unexplored. In this paper, we contribute to the literature by studying how policies that alter trade barriers – including existing global tariffs, global tariff reform scenarios, and transportation efficiency targets – impact global CO_2 levels.

Our analysis uncovers the importance of changes in the use and transportation of intermediate inputs in determining the emissions consequences of reduced trade barriers. Reduced trade barriers lead to increased gross output relative to value added, and this effect contributes towards a substantial increase in transportation emissions because these emissions depend directly on the gross flow of goods. Put differently, a reduction in trade barriers effectively entails an increase in shipping per unit of final output. Changes in the pattern of intermediate input use also play a key role in accounting for the increase in production/consumption emissions in response to reduced trade barriers. Reduced trade barriers increase wages relative to the prices of other goods, which means that from a producer perspective labor becomes more expensive relative to intermediate inputs. The resulting increase in the quantity of intermediates relative to labor in production increases emissions per value added for two reasons. First, this logic applies directly to fossil fuels – which are a subset of intermediate inputs – and second, because fossil fuels are more generally embodied in other intermediate inputs.

We quantify these channels using a multi-country, multi-sector quantitative general equilibrium framework with detailed global input-output linkages and with transportation costs that are determined by endogenous fuel prices. Emissions are generated in the model when fossil fuels are used in production, consumption or for domestic or international transportation. This framework allows us to capture various channels through which trade barriers might potentially affect emissions, including re-allocation of activity across countries and sectors, and changes in the price and quantity of inputs, including fossil fuels. Using the parsimonious "exact hat algebra" methodology from Dekle et al. (2008), we explore the impacts of existing global tariffs, improvements in transportation efficiency and a range of tariff reform scenarios.

We first analyze how existing global tariffs affect CO_2 emissions by evaluating a hypothetical scenario where all tariffs are removed. We find that tariff elimination would increase global GDP by 0.5% and global emissions by 1.8%, implying that trade liberalization would lead to emissions increases beyond the mechanical "scale" effect of the global output increase.[1] Production/consumption and transportation emissions each account for half of the increase in total emissions. Tariff removal increases international transportation emissions and decreases domestic transportation emissions, together leading to an 5.33% increase in total transportation emissions. A decomposition reveals that a substantial portion of this increase is due to the expansion in gross output relative to value added, which can also be interpreted as a lengthening of value chains (Fally 2012). Production emissions increase by 1.22%, and this increase is directly related to the increased use of intermediate inputs on account of the reduction in their price relative to labor. If labor-intermediate substitution is "shut down" using a Leontief version of the model, the production emissions increase is entirely wiped out. Hence, the increased emissions here are due to the substitution towards intermediate inputs that are induced by the increase in wages relative to the prices of other goods.

While our results overall imply that tariffs can lead to decreased emissions that proportionately exceed the output decrease, this does not, however, imply that tariffs are likely to be a desirable mitigation instrument. The implied mitigation costs of existing tariffs for example – around 550 $\$/tCO_2$ – are far above other policy options (Gillingham and Stock 2018). Even if we value the negative externality from carbon emissions at 200 $\$ \, tCO_2$, which is a relatively high value suggested by the current literature (Daniel et al. 2019; Hänsel et al. 2020), the benefit of the output increase from tariff reductions easily exceeds the externality costs.

Motivated by the prevalence of efforts aiming to reduce the fuel intensity of transportation, we next study the global CO_2 implications of improvements in transportation efficiency.[2] As expected, we find that projected improvements in transportation efficiency reduce transportation emission substantially. However, these improvements tend to increase

[1]Our main results extend to a scenario where we liberalize non-tariff barriers to trade in the same manner as tariffs. We treat the more speculative analysis of non-tariff barriers as a check of our main results due to the strong assumptions underlying the analysis of these forms of protection.

[2]The International Air Transport Association and the International Maritime Organization have stated targets related to energy efficiency improvements for international air and sea transport respectively. Many countries have programs targeting the energy efficiency of road transport (c.f., the U.S. Department of Energy's Super Truck II program).

production emissions by a comparable or even larger magnitude, generally implying relatively modest decreases (or possible increases) in total emissions. Most of the increase in production emissions is again explained by the labor-intermediate substitution channel. On the other hand, the reduction in transportation emissions in response to the efficiency improvements is only modestly tempered by the value chain lengthening. The lengthening effect for efficiency improvements is much weaker than for tariffs for two reasons. First, efficiency improvements induce shifts towards sectors with shorter value chains because fuel costs for transportation tend to be higher on upstream, and therefore shorter value chain, sectors. Second, unlike with tariffs, the global GDP increase from improved transportation efficiency is partially due the effective freeing up of resources previously spent on transportation, an effect that causes a relatively proportionate increase in gross output to value added and in turn mutes changes in value chain lengths.

We also analyze the emissions consequences of various partial tariff liberalization scenarios. While 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 situation where tariffs are higher on goods that tend to be used more for final consumption than as inputs – can, up to a point, increase global welfare with a very small increase in CO_2. This is because such policies limit the expansion of gross output relative to value added by concentrating tariff cuts on goods that are less likely to be used as inputs. There are broadly comparable effects from partial liberalization schemes that focus on reducing higher initial tariffs, such as a "Swiss Formula" approach that entails proportionately greater tariff reductions on initially higher tariffs or reducing "tariff peaks" – tariffs that are substantially higher than average.

Our paper is related to several strands of the trade and environment literature. In analyzing how trade barriers affect transportation emissions, our paper is especially connected to Shapiro (2016) and Cristea et al. (2013). Both papers quantify the increased emissions that results from goods traveling further when trade costs are reduced. Shapiro especially emphasizes the substitution from domestic to international transportation, while Cristea et al. highlight the fact that tariffs tend to be higher between more distant countries. While these mechanisms are present in our analysis as well, we uncover the key role of intermediate input trade in magnifying the emissions consequences of reduced trade barriers. Reducing trade barriers increases transportation emissions in substantial part by expanding the amount of gross flows for the same value added. In interpreting this channel as the lengthening of value chains, our work illustrates a key connection between the trade and environment literature and the literature on value chains (e.g., Johnson (2018)).[3] Our

[3] The value chain lengthening interpretation also points to a channel through which energy efficiency

paper is also closely connected to Shapiro (2021), who documents and explains a negative environmental bias – tariffs are higher on relatively cleaner downstream vs. relatively dirtier upstream industries – in the structure of existing tariffs and notes that undoing this bias could lead to carbon-negative increases in global GDP. Our paper complements Shapiro (2021) first, by emphasizing the interaction between tariffs, intermediate input use and emissions from transportation as noted above, a relationship that cannot directly be disentangled in Shapiro's framework. Second, even in connection with production emissions, we highlight a channel that functions through labor-intermediate substitution and is, therefore, distinct from Shapiro's point, which is about the structure of tariffs *across* goods. The labor-intermediate effect we emphasize does not rely on pre-existing tariff patterns and therefore would more generally apply to any policies or trends that differentially affect the price of labor vs. intermediate inputs.

Unlike each of these papers, we study the impacts of reductions in tariffs and in natural trade barriers due to energy efficiency improvements. Our analysis therefore brings new insights to a broader literature that contrasts trade barriers (e.g., Felbermayr et al. (2015); Besedes and Cole (2017); Jiao and Wei (2020)) by showing that tariffs and natural trade barriers have differential impacts on value chains and environmental outcomes, due to both fundamental differences in how these barriers affect output and systematic difference in the pattern of the barriers. Pothen and Hübler (2018) also study the CO_2 impacts of different types of trade barriers, but they do not emphasize the comparison across types of barriers, changes in transportation emissions or changes in value chains.

More broadly within the trade and environment literature the overarching theme – whether in the context of the pollution haven hypothesis, trade liberalization (e.g., Grossman and Krueger (1993), Antweiler et al. (2001), Cherniwchan (2017)) or hypothetical carbon tariffs (e.g., Böhringer et al. (2015), Larch and Wanner (2017)) – has been on studying the environmental consequences of the geographical and industrial reallocation of economic activity as a result of trade-related policies. Our work complements this general emphasis by uncovering a distinct channel linking trade policy to GHGs that is not directly about sectoral or regional reallocation, namely, that trade policy instruments such as tariffs affect the use and transportation of intermediate inputs. We show that these intermediate input channels also play an important role in determining the effect of hypothetical carbon tariffs.

Beyond the trade and environment literature, our work helps inform the broader question of the effect of non-climate policies and trends on GHGs. As noted in National Research

improvements can induce increases in energy use (i.e., a "rebound effect"). The value chain lengthening channel is distinct from the energy price and growth channels emphasized in the literature on macroeconomic rebound effects (Gillingham et al. 2016).

Council (2013), there is limited research on how non-carbon policies, other than energy related policies, influence GHG emissions. The exploratory work in this report finds that broad-based tax incentives in the US influence GHGs almost exclusively through changes in GDP. In contrast, 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 taxes on intermediate inputs. More generally, any policy that differentially affects the cost of labor vs. material inputs – such as wage subsidies or minimum wage policies – are likely to have emissions consequences through the labor-intermediate channel we identify. Finally, beyond specific policies, our analysis reveals potential environmental consequences of global production structures that affect the level of gross vs. value added output and trade flows (e.g., Johnson and Noguera (2012) or Johnson and Noguera (2017)).

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 5 present and analyze our results and Section 6 concludes.

2 Model

2.1 Framework

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 country's 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 using Cobb-Douglas technology. The intermediate inputs are sourced from all sectors and across the world, so the model features global value chains. The "roundabout production" approach that we rely on is the standard way to model global value chains in the literature (Antras and Chor 2021). CO_2 emissions are generated by the use of fossil fuels in production, consumption and transportation. We treat CO_2 as a pure externality – so consumers take CO_2 levels as given – that generates disutility that is separable from the utility from consumption.[4]

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

2.1.1 Government

Each country imposes ad-valorem tariffs on imports. τ_{ij}^{s} is the ad-valorem tariff rate faced by imports of product s from country i in country j. Note that in the case where $i = j$, the tariff rate will be equal to zero, i.e. $\tau_{ii}^{s} = 0$.[5] Tariff revenue, $R_j = \sum_s \sum_i \tau_{ij}^{s} \frac{X_{ij}^{s}}{1+\tau_{ij}^{s}}$ where X_{ij}^{s} is j's total expenditure on s from i, is rebated to households.

2.1.2 Households

Households have a Cobb-Douglas utility over goods and a CES sub-utility over varieties from different sources. The utility function is:

$$U_j = \left[\prod \left(Q_j^s\right)^{\beta_j^s}\right] \times \Delta_j\left(E\right), \tag{1}$$

where β_j^s is the Cobb-Douglas share of household consumption on good s in country j; $\Delta_j\left(E\right)$ is the externality from global emissions and Q_j^s – the quantity of s consumed in j – is itself a CES aggregate given by:

$$Q_j^s = \left[\sum_i \left(\lambda_{ij}^s\right)^{\frac{1}{\epsilon^s}} \left(Q_{ij}^s\right)^{\frac{\epsilon^s-1}{\epsilon^s}}\right]^{\frac{\epsilon^s}{\epsilon^s-1}}, \tag{2}$$

where Q_{ij}^s is the quantity of i's variety of s consumed in j and λ_{ij}^s is a quality or taste parameter for i's variety of s in country j. Household income includes wage income, rebated tariff revenues (R_j) and an exogenous trade imbalance term (D_j):

$$X_j = w_j L_j + R_j + D_j, \tag{3}$$

where L_j and w_j are the labor endowment and wage of country j, respectively. D_j is aggregate net imports in j, which is assumed fixed. The household maximizes utility subject to this budget constraint, taking as given the CO_2 externality. This gives us the household expenditure in j on i's variety of good s:

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

where X_j is the total expenditure in country j and P_j^s is the CES price index:

$$P_j^s = \left[\sum_k \lambda_{kj}^s {p_{kj}^s}^{1-\epsilon^s}\right]^{\frac{1}{1-\epsilon^s}}. \tag{5}$$

[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.

2.1.3 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.

As we elaborate in the results section, the substitution between labor and intermediate inputs will play an important role in determining the effects of trade barriers on emissions. In our baseline analysis, we follow the general practice in the literature by using a Cobb-Douglas functional form (e.g., Caliendo and Parro (2015)) that implies a unitary elasticity of substitution between labor and intermediate inputs. Estimates from the literature suggest that assuming Cobb-Douglas is reasonable (Atalay 2017), but we also explore non-unitary elasticities of substitution in sensitivity analyses.[6] In order to shed light on how labor-intermediate substitution affects emissions, we also compare our main results to results from a version of the model with a Leontief functional form between labor and intermediate inputs, which effectively tells us what would happen if we were to completely shut down this substitution.

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 – which excludes transportation – of s from i will be the Cobb-Douglas unit cost function:

$$p_i^s = \frac{1}{A_i^s}\overline{\alpha}_i^s \left(\frac{w_i}{\alpha_i^s}\right)^{\alpha_i^s} \left[\frac{1}{1-\alpha_i^s}\prod_{\tilde{s}}\left(\frac{P_i^{\tilde{s}}}{\omega_i^{\tilde{s}s}}\right)^{\omega_i^{\tilde{s}s}}\right]^{1-\alpha_i^s} \tag{6}$$

[6] Atalay estimates values of 0.84 and 0.88 with standard errors of 0.44 and 0.35 using OLS and IV respectively.

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; and $\prod_{\tilde{s}}\left(\frac{P_i^{\tilde{s}}}{\omega_i^{\tilde{s}s}}\right)^{\omega_i^{\tilde{s}s}}$ is the price of the intermediate input bundle for sector s in country i.[7]

2.1.4 Transportation Costs

In evaluating the effect of trade barriers on CO_2, it is important to account for the use of fossil fuels in both domestic and international transportation. We incorporate this into the model explicitly by assuming that transporting goods requires the use of refined petroleum – a category which includes the various liquid fuels used for transport (e.g., diesel and residual fuel oils and aviation fuels) – which is one of the goods in the model, and whose price therefore endogenously responds to equilibrium changes. Specifically, transporting a physical unit of output from sector s from country i to j requires $\phi_{ij}^{ms} \geq 0$ units of good m (again a CES aggregate across origins that is assumed to be identical to the one for consumption and broader firm usage). The notation here is much more general than it needs to be in that $\phi_{ij}^{ms} = 0$ for m other than refined petroleum, but this generality will be useful in laying out our equilibrium conditions in a more parsimonious way.[8]

To account for other types of transportation costs and trade frictions, we also allow for iceberg trade costs as in much of the international trade literature. The price at destination j, which will take into account both types of trade costs and tariffs, is:

$$p_{ij}^s = \left(p_i^s d_{ij}^s + \sum_m \phi_{ij}^{ms} P_i^m\right)\left(1 + \tau_{ij}^s\right), \tag{7}$$

where $\sum_m \phi_{ij}^{ms} P_i^m$ are per unit expenditures on goods for transportation and $d_{ij}^s \geq 1$ are the iceberg costs associated with delivering a good from i to j. In keeping with the GTAP database's accounting and common practice in most countries, we assume tariffs are applied on the price inclusive of freight expenses.

[7] A recent literature (e.g., Ganapati et al. (2020)) suggests that changes in input prices, particularly fossil fuels, may not be fully passed through into the final price of a good, due to substitution across inputs and market power. Pass-through is incomplete in our framework due to substitution across inputs, but like standard structural gravity models – whether featuring perfect competition or monopolistic competition with constant markups – our framework does not capture the market power channel.

[8] Our assumptions here imply that fuel costs changes are fully passed on to transportation expenses. In our sensitivity analysis section, we discuss this point further and argue that this is not likely to substantially affect our results.

2.1.5 Equilibrium

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

$$X_{ij}^{st} = \lambda_i \left(\frac{p_{ij}^s}{P_j^s}\right)^{1-\epsilon^s} \left[\left(1-\alpha_j^t\right)\omega_j^{st} X_j^t\right]. \tag{8}$$

where X_j^t is the total value of sector t in country j excluding expenditures on transportation. Total expenditure by firms in i on good m for transport is:

$$X_i^{m,T} = \sum_j \sum_s P_i^m \frac{X_{ij}^s}{p_{ij}^s} \phi_{ij}^{ms}. \tag{9}$$

Using equations (4), (8) and (9), total expenditure in j on s from i is:

$$X_{ij}^s = \alpha_i \left(\frac{p_{ij}^s}{P_j^s}\right)^{1-\epsilon^s} \left\{\beta_j^s X_j + \sum_t \left(1-\alpha_j^t\right)\omega_j^{st} X_j^t + X_j^{s,T}\right\} \tag{10}$$

and the transportation exclusive total value of sector s in country i is:

$$X_i^s = \sum_j \frac{X_{ij}^s}{1+\tau_{ij}^s} - \sum_j \sum_m P_i^m \frac{X_{ij}^s}{p_{ij}^s} \phi_{ij}^{ms}. \tag{11}$$

Equilibrium requires total wages to equal expenditures on labor – revenue in each sector scaled by the labor share – in each country:

$$\sum_s X_i^s \alpha_i^s = w_i L_i. \tag{12}$$

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 to evaluate the effect of a change in global tariffs or improvements in efficiency.[9] Once this method is applied, the only parameters we require are the trade elasticities for each sector, per unit expenditures for transportation, and various shares that can be calculated directly from the baseline 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 $\hat{X}_{ij}^s \equiv X_{ij}^{\prime s}/X_{ij}^s$, where $X_{ij}^{\prime s}$ is the counterfactual

[9] Here we derive the expressions for counterfactual tariffs but comparable expressions can be obtained for changes in transportation efficiency, which are modeled as changes in ϕ_{ij}^{ms}.

value of X_{ij}^s.

For counterfactual tariffs the relevant proportional changes in prices are:

$$\hat{p}_{ij}^s = \left(\hat{w}_i^{\alpha_i^s} \left[\prod_{\tilde{s}} \left(\hat{P}_i^{\tilde{s}} \right)^{\omega_i^{\tilde{s}s}} \right]^{1-\alpha_i^s} \frac{1 - \sum_m p_{ij}^{sm}}{p_{ij}^s / \left(1 + \tau_{ij}^s\right)} + \sum_m \hat{P}_i^m \frac{p_{ij}^{sm}}{p_{ij}^s / \left(1+\tau_{ij}^s\right)} \right) \hat{T}_{ij}^s \tag{13}$$

$$\hat{P}_j^s = \left[\sum \frac{X_{kj}^s}{X_j^s} \left(\hat{p}_{kj}^s\right)^{1-\epsilon^s} \right]^{\frac{1}{1-\epsilon^s}} \tag{14}$$

where $\hat{T}_{ij}^s = \frac{1+\tau_{ij}^{\prime s}}{1+\tau_{ij}^s}$ and $p_{ij}^{sm} = P_i^m \phi_{ij}^{sm}$ is per unit expenditure on m from transporting s from i to j.

Proportional changes in expenditures and income are:

$$\hat{X}_{ij}^s = \left(\frac{\hat{p}_{ij}^s}{\hat{P}_j^s} \right)^{1-\epsilon^s} \left\{ \hat{X}_j \frac{\beta_j^s X_j}{\sum_i X_{ij}^s} + \sum_t \hat{X}_j^t \frac{\left(1-\alpha_j^t\right) \omega_j^{st} X_j^t}{\sum_i X_{ij}^s} + \hat{X}_j^{s,T} \frac{X_j^{s,T}}{\sum_i X_{ij}^s} \right\} \tag{15}$$

$$\hat{X}_j = \hat{w}_j \frac{w_j L_j}{X_j} + \frac{D_j}{X_j} + \sum_s \sum_m \frac{X_{mj}^s}{X_j} t_{mj}^{\prime s} \hat{X}_{mj}^s \tag{16}$$

$$\hat{X}_i^s = \sum_j \hat{X}_{ij}^s \frac{\frac{X_{ij}^s}{1+\tau_{ij}^s}}{X_i^s} - \sum_j \sum_m \hat{P}_i^m \frac{\hat{X}_{ij}^s}{\hat{p}_{ij}^s} \frac{X_{ij}^{ms,T}}{X_i^s} \tag{17}$$

$$\hat{X}_i^{m,T} = \sum_j \sum_s \hat{P}_i^m \frac{\hat{X}_{ij}^s}{\hat{p}_{ij}^s} \frac{X_{ij}^{ms,T}}{X_i^{m,T}} \tag{18}$$

where $t_{mj}^{\prime s} = \frac{\tau_{mj}^{\prime s}}{1+\tau_{mj}^{\prime s}}$ and $X_{ij}^{ms,T} = P_i^m \frac{X_{ij}^s}{p_{ij}^s} \phi_{ij}^{ms}$.

Equations (13)-(18) and the equilibrium condition (12) determine counterfactuals. Equations (13) and (14) determine price levels for a given vector of proportional changes in wages, while the remaining conditions determine wages.[10] The model can be reduced to an N by N system using an algorithm that we describe in the appendix.

2.3 Emissions

Emissions are generated by the use of fossil fuels for production, consumption or transportation, which follows best practice. In models with intermediate inputs like ours, it is standard in the economics (Pothen and Hübler 2018; Shapiro 2021) and environmental science (Hendrickson et al. 2006) literature to account for emissions based on the use of fossil fuels.[11] Since our model allows for substitution across labor and material and across

[10] We normalize the global wage: $\sum_j w_j' L_j = \sum_j L_j$.

[11] This accounting naturally matches the true emissions generating process for CO_2 (i.e., the combustion of fossil fuels) and is consistent with IPCC guidelines (IPCC 2006). Models that do not explicitly model fossil fuels would need to assume emissions are proportional to output or value added, but even in these models

intermediate inputs, a sector's emission intensity (i.e., emissions per unit value added or gross output) will not be constant and its emissions will not be proportional to output. As we discuss below, the standard decompositions of the environmental impacts of trade do start by conceptualizing a sector's emissions as its value-added (or output) multiplied by an emissions intensity (Copeland et al. 2022), but this starting point is distinct from the actual emission generating process.

Global emissions are:

$$E = \underbrace{\sum_j \sum_s \sum_t Q_j^{st} \kappa_j^{st}}_{EP} + \underbrace{\sum_i \sum_j \sum_s Q_{ij}^{s} \kappa_{ij}^{s}}_{ET} \tag{19}$$

The first term on the right-hand side represents global emissions from production and consumption (EP). It is the sum across countries, input sectors, and using sectors (including household use) of the quantity of goods from sector s used by sector t in country j, $Q_j^{st} = \frac{X_j^{st}}{P_j^{st}}$, multiplied by the emissions generated per unit of that input, κ_j^{st}. Note that, while κ_j^{st} is defined for all values of s, it will only be non-zero for fossil fuels. 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 feedstock as opposed to being combusted (e.g. crude oil used in crude oil refining or natural gas used in chemical manufacturing). The constant κ_j^{st} means that the emissions generated per unit of a fossil fuel used in a particular industry is not affected by counterfactual changes. However, the emissions intensity of an industry is not constant because firms will adjust their use of labor vs. intermediates and the composition of intermediates (including fossil fuels) in response to changes in input prices.[12]

The second term on the right-hand side is global emissions from transportation (ET). It is the sum across all trade flows (domestic and international) of the quantity of goods shipped, Q_{ij}^{s}, multiplied by emissions per unit shipped, κ_{ij}^{s}. Emissions per unit shipped on each trade flow depends on fuel expenditures for transport according to $\kappa_{ij}^{s} = \sum_m \phi_{ij}^{ms} \kappa^{mT}$, where κ^{mT} are the emissions generated per unit of good m used for transportation.

2.4 Emissions Decompositions

The trade and environment literature frequently uses decomposition exercises to isolate the mechanisms driving changes in environmental effects. On the production side, it is

emissions factors are calculated based on sectors' baseline use of fossil fuels (Cristea et al. 2013; Shapiro 2016).

[12]Our analysis does not incorporate potential non-price channels for changes in emissions intensity as a result of trade (e.g. adoption of cleaner technologies in response to trade policy changes as in Imbruno and Ketterer (2018) or effects through national income changes in the spirit of the environmental Kuznets curve). Such channels could potentially attenuate emissions increases due to trade but should not affect our broader point about the importance of the use and transport of intermediates in an obvious way.

standard to break down changes into scale, composition and technique effects (e.g., Copeland and Taylor (1994)). In this decomposition the scale effect captures emissions due to changes in total value added, the composition effect captures emissions due to reallocation of value added across countries and sectors, and the technique effect captures emissions due to changes in emissions intensity per unit value added at the country-sector level. The primary mechanism we emphasize in terms of production emissions – labor-material substitution – is not sharply isolated by this standard decomposition. As mentioned above, we therefore isolate the contribution of labor-material substitution to changes in emissions by comparing emissions outcomes to those from a version of the model that imposes a Leontief functional form between labor and intermediate inputs. This analysis directly isolates how emissions would change if labor-intermediate substitution at the firm level is completely shut down. However, we also report scale, composition and technique effects in supplemental tables and show that the effects of labor-intermediate substitution is largely captured by the technique effect.[13]

For transportation emissions, we develop a new decomposition that can help shed light on the consequences of changes in value chains. In the presence of global value chains, and trade in intermediate inputs more generally, reductions in trade barriers can result in greater emissions increases than if an equivalent increase in value added took place without these production linkages. Suppose, for example, that intermediate inputs worth \$100 are exported from country A to country B, where it is combined with components worth \$10 and then exported back to the A. Abstracting from weight differences, the emissions generated under this scenario will be much greater than if \$10 worth of goods that were produced entirely in B were exported to A.

This simple example makes clear that the emissions associated with transport are closely connected to the ratio of gross output to value added. To formalize this insight, we can write transportation emissions per unit of value added as $\frac{ET}{V} = \frac{ET}{Q} * \frac{Q}{V}$ where Q is real gross output and V is real value added. We can therefore decompose changes in transportation emissions as:

$$\frac{d\,(ET/V)}{ET/V} = \frac{d\,(ET/Q)}{ET/Q} + \frac{d\,(Q/V)}{Q/V} \tag{20}$$

The first term captures the percent change in transportation emissions per unit of output produced (and therefore transported), which can be thought of as the emissions intensity of transport. This term includes the effects highlighted in the literature by Shapiro (2016) and Cristea et al. (2013). For example, if changes in trade barriers increase transportation emissions by causing goods to travel greater distances, this will be reflected in a higher

[13] We present a Copeland and Taylor style decomposition following Cherniwchan et al. (2017) using our notation in the appendix.

ET/Q.[14]

The second term is the percent change in the global ratio of gross output to value added. This term captures specifically the effect we emphasize, namely the consequence of lengthening value chains. The ratio of gross output to value added is commonly used to measure the evolution of value chains over time (e.g., Johnson (2018)) and Fally (2012) also notes that in a closed economy Q/V can be interpreted as a measure of the average vertical integration of value chains, or the average length of value chains. To see this, note that in a closed economy, which we can interpret the world as a whole to be, $\frac{Q}{V} = \frac{\sum_{is} C_i^s \tilde{Q}_i^s}{\sum_{is} C_i^s}$, where C_i^s is final consumption of good is and $\tilde{Q}_i^s$ is the gross output embodied per unit of final consumption of good is. A key insight in Fally (2012) is that $\tilde{Q}_i^s$ measures the number of sector/border crossings embodied in the production of the final good, or the vertical length of the good's value chain.[15] Therefore, the gross output-value added ratio is effectively an index that measures a global weighted average vertical integration (or length) of value chains.

An increase in the average length of value chains can operate through two channels: shifts in final consumption shares towards goods that have longer value chains, or lengthening of goods' value chains. We can isolate these two channels as follows: $d\left(Q/V\right) = \sum_{is} d\left(\frac{C_i^s}{\sum_{is} C_i^s}\right) \tilde{Q}_i^s + \left(\sum_{is} \frac{C_i^s}{\sum_{is} C_i^s}\right) d\tilde{Q}_i^s$. The first term captures changes in the composition of final consumption while holding the length of individual value chains fixed, while the second captures changes in the length of individual value chains while holding the composition of final consumption fixed.[16] As we discuss more in connection with our results, value chain lengthening and the mechanism we emphasize on the production side are inherently linked because the length of an individual sector's value chain depends partly on the use of intermediate inputs relative to labor in that sector and all associated input sectors.

[14] In supplementary tables we decompose the changes in the emissions intensity of transportation. Emissions per unit of output is $ET/Q = kg/Q * kgkm/kg * ET/kgkm$, where kg is the total weight of products shipped and $kgkm$ is global transportation services provided in kilogram-kilometers. With this decomposition we can explore how changes in weight per dollar of gross output, changes in transportation services per kilogram shipped, and changes the emissions intensity of transportation services contribute to changes in the overall emissions intensity of transport.

[15] A simple example illustrates this logic. Suppose there are two goods: good A, which is produced entirely from labor and good B, which is produced from equal shares of labor and good A. $\tilde{Q}_A = 1$ because the production of good A does not use intermediate inputs and therefore embodies only one stage of production. The gross output embodied in good B equals $\tilde{Q}_B = 1 + 0.5 * 1 = 1.5$ because each dollar of B produced requires \$0.5 of A. In terms of embodied production stages, combining labor and good A is one production stage, and half of gross output is made up of an intermediate input with one stage of production. The input-output methods described below generalize these calculations.

[16] Following Fally (2012), we calculate $\tilde{Q}_i^s$ using input-output methods. If we define A as an $N*S$ by $N*S$ matrix that describes the dollars of sector is used by sector jt to produce a dollar of output (A has elements $\frac{X_{ij}^{st}}{X_j^t}$), then $\tilde{X} = \mathbf{1'} * (I - A)^{-1}$ where $\mathbf{1}$ is an $N*S$ by 1 vector of ones and I is an $N*S$ by $N*S$ identity matrix. That is, $\tilde{Q}_i^s$ are the column sums of the Leontief inverse matrix.

3 Data

3.1 Baseline Data

Baseline values for bilateral trade flows, country input-output tables, tariff rates 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.1) and 20 sectors (Table A.2). Our sector aggregation follows Shapiro (2021). Each fossil fuel (coal, crude oil, natural gas, refined petroleum) is kept as a single sector, while the remaining sectors are aggregated.

The household expenditure shares (β_j^s), value added (α_j^s) and intermediate input (ω_j^{st}) expenditure shares can be directly calculated from the GTAP database.[17] 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.[18] We winsorize emissions per 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.

3.2 Transportation

Fuel use from transportation depends on the weight of the goods being moved, the distance being traveled and the mode of transport (air, rail, road, sea) being used. Following the literature (Cristea et al. 2013; Shapiro 2016) we calculate the per unit expenditures on fuel for transporting good s from i to j as:

$$\phi_{ij}^s = \xi_{ij}^s \sum_k s_{ijk}^s km_{ijk} x_k \tag{21}$$

where ξ_{is}^s are weight-to-value ratios; s_{ijk}^s are mode shares; km_{ijk} is distance traveled between i and j on mode k; and x_k are expenditures on fuel per unit distance-weight by mode share. The index m is dropped for clarity.[19]

We assemble data from a number of sources to obtain ϕ_{ij}^s. For air, rail and road modes we use population weighted shortest path (i.e., great circle) distances between the top 25

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

[18] These emissions measures capture only energy related CO_2 emissions, which account for roughly 65% of global GHG emissions (US EPA 2016). 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.

[19] Since this structure accounts for transportation expenditures and CO_2 by firms, we set expenditure shares on transportation in all industries to zero when constructing ω_j^{st}. We capture household expenditures of transportation services by maintaining transportation as a producing sector and allowing household expenditure shares on transportation to be positive.

most populated cities for pairs of countries from CEPII (Mayer and Zignago 2011). Domestic (intranational) land distances distances are calculated in an equivalent manner. We obtain sea distances from Bertoli et al. (2016), which are based on observed shipping routes and assumptions about the ports used for each bilateral route.[20] For regions that aggregate countries we use average bilateral distances across countries in the region weighted by GDP. The Bertoli et al. (2016) database does not include domestic sea distances, so we approximate these by scaling up domestic land distances by 1.96, which is the GDP weighted average ratio of international sea to land distances between contiguous countries in our dataset.

Mode shares and weight-to-value ratios are from Cristea et al. (2013). The Cristea et al. (2013) data reports values for 27 GTAP sectors and 40 regions (28 individual countries and 12 aggregated regions), which we assign to our sectors and regions. We also construct mode shares for domestic trade from the Cristea et al. (2013) data. Additional details about these calculations are provided in the Appendix.

To obtain x_k, we divide estimates of tCO_2 per t-km by mode from Cristea et al. (2013) by the global average tCO_2 per dollar expenditure on refined petroleum by the transportation sector from the GTAP data base.[21] This ensures consistency between emissions generated and total expenditures on fuel by the transportation sector.

3.3 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 (2021), 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.

3.4 Summary Statistics

Table 1 also provides information about several baseline values of interest by sector and for households. The sectors vary substantially in terms of total value (second column of

[20] Since ships must travel around land and to/from specific ports, shortest path distances may greatly understate actual distances traveled.

[21] The specific values are 552, 22.7, 119.7, and 7 gCO_2 per t-km for air, rail, road and sea respectively, which is the low scenario from Cristea et al. (2013). For sea transport we use an average for bulker and container ships. As a sensitivity analysis we use mode specific emissions factors from the high scenario, which is also consistent with the factors uses by Shapiro (2016). The tCO_2 per dollar value used to convert these values to expenditures also serves as the emissions factor κ for refined petroleum expenditures for transportation.

numbers) and in terms of the share of intermediate input usage to total output value (third 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. The fourth column of numbers ($\tilde{Q}$) reports consumption weighted average value chain lengths by sector. Value chains are shortest for upstream sectors, like raw materials, and there is a clear positive relationship between intermediate input shares and value chain lengths.

In the remaining columns, we attribute production/consumption and transportation CO_2 to sectors using three methods, each of which provides a reasonable way to quantify a sector's contribution to global CO_2. Used CO_2, the 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 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.

The Using CO_2 column reports direct emissions from the use of fossil fuels by each sector. As expected, transportation and electricity production are the largest sources of emissions. Total transportation CO_2 are determined by our detailed accounting of transportation fuel use and is consistent with other estimates Shapiro (2016), after adjusting for differences in baseline trade flows. CO_2 due to fuel use for transportation is broken down by producing sector in the "Transport" column (i.e., CO_2 from transporting minerals to metal production are attributed to the minerals sector). For most sectors CO_2 from transport is of the same magnitude as CO_2 generated by the use of fossil fuels in production. In Table A.3 we show that the average CO_2 intensity (CO_2/\$) of international transport tends to be considerably higher for upstream sectors (e.g., coal and minerals). This pattern is more closely related to the weight of the goods being transported than to distances traveled.

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 including transportation. 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.4 for details). Embodied emissions are much more balanced across sectors than the direct and using emissions because the embodied emissions spread the emissions the production of intermediate inputs (e.g., electricity) to the sectors that use these goods. 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. The distribution of using and embodied CO_2 across sectors makes clear that all tariffs, not just those on fossil fuels, can have CO_2 implications.[22]

The implications of sectoral shifts induced by reductions in trade barriers depend partly on pre-existing correlations between trade barriers and emissions intensities and value chain lengths. In the first row in Figure A.1, we show that existing tariffs are higher on goods with lower embodied CO_2 and longer value chains. The former pattern reflects the "negative environmental bias" emphasized by Shapiro (2021), while the latter pattern reflects tariff escalation. Tariff escalation, which is a likely explanation for the negative environmental bias in tariffs, refers to the common situation where tariffs increase along processing chains, or that tariffs on upstream sectors tend to be lower than tariffs on downstream sectors. In the second row in Figure A.1, we show that transportation costs are also higher on goods with lower embodied emissions – although this patterns is somewhat weaker than for tariff – but that transportation costs are higher for goods with shorter value chains like heavy raw materials. We therefore expect that reductions in either tariffs or transportation costs to lead to a reallocation away from carbon intensive sectors. However, reductions in tariffs will induce shift towards sectors with longer value chains, while reductions in transport costs will induce shifts towards sectors with shorter value chains.

4 Impact of Reducing Trade Barriers

4.1 Reducing Tariffs

In order to understand how current tariffs affect global emissions, it is natural to first 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 2. Additional results and decompositions for this counterfactual are reported in Table A.5. Removing global tariffs increases global CO_2 by 1.8% and increases real income by 0.50%.[23] Transportation and production/consumption emissions each account for half of the total emissions increase. Both increase by more than the scale effect, with transportation emissions

[22]In the Appendix, Table A.4, we report CO_2 totals for the top 20 emitting countries using similar allocation methods. China and the US are by far the top two contributors to CO_2. When allocating by using sector, China and the US have comparable emissions, but the US is the largest contributor to CO_2 when using embodied CO_2. 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.

[23]In our framework, global equivalent variation (EV) is equivalent to the change in global real GDP. Despite differences in modeling frameworks and data, these numbers are broadly comparable to Pothen and Hübler (2018) and Shapiro (2021).

increasing by 5.31% and production emissions by 1.22%.

We first examine the change in transportation emissions. The increase in transportation emissions per global value added is 4.81%. We use (20) to further break down this increase. Transportation emissions per value added could increase because of increased emissions for the same gross flows or because of increased gross flows used in the production of the same value added. The former term is captured by the ET/Q effect, which accounts for a 2.76% increase in transportation emissions per value added out of the 4.81% total. We report the decomposition of the ET/Q effect in Table A.5, which shows that the increase in ET/Q, both on aggregate and for international transport only, is largely driven by increases in the average distance traveled per unit of goods shipped. This point, that trade barrier reductions would simply cause goods to travel further on average, is highlighted by Cristea et al. (2013) and Shapiro (2016). Cristea et al. (2013) note that this pattern could reflect that existing tariffs tend to be lower on trade partners that are geographically closer due to the prevalence of regional trade agreements. Our results also suggest that tariff removal reduces the weight of transported goods – because tariffs tend to be higher on downstream, and lighter, products – and reduces the emissions intensity of shipping, which is consistent with increases in maritime transport due to increases in international trade.

We emphasize an effect that is distinct from changes in how goods are transported. Since transportation emissions depend directly on the gross flows of goods across locations, an increase in gross flows for the same value added would also increase emissions. This effect, which to our knowledge has not be previously highlighted in the literature, is captured by the Q/V term. This term accounts for a 2.76% increase in transportation emissions per value added out of the total 4.81%, and therefore is a substantial reason for the increased emissions in response to reduced tariffs. As noted by Fally (2012), the Q/V term can also be interpreted as a measure of the average number of stages of production and therefore directly captures emissions resulting from the lengthening of value chains.

Decomposing the Q/V term, we see that the lengthening effect, changes in value chain lengths given the composition of final consumption, accounts for the bulk (1.84% out of the 1.99%) of the increase in the average length of value chains. This is intuitive since tariff reduction should directly affect incentives to ship intermediate goods across borders.

Turning to production emissions, these emissions also increase substantially (1.22%) and indeed by more than the scale effect, implying that production emissions per value added globally also rises. As we note in the theory, intermediate inputs are likely to play a role in this effect as well. The tariff removals leads to a reduction in the price of intermediate goods relative to wages – or equivalently, an increase in wages relative to the price of intermediate goods.[24] The ensuing substitution would increase the usage of intermediate inputs, thereby also increasing emissions. We can evaluate the importance of this channel by considering a version of the model with a Leontief relationship between labor and intermediates, which effectively shuts down the substitution between labor and intermediates at the sector level.[25]

The change in production emissions under the Leontief assumption is reported in Table 2 in the 'L-M fixed' row. We see that when labor-intermediates substitution is cut off, the increase in production emissions is wiped out and in fact turns into a reduction of -0.51%.[26] The decrease in emissions here is remarkable in that it is net of the positive scale effect. This is consistent with a shift towards goods with lower embodied emissions that would result from the negative environmental bias of tariffs noted by Shapiro (2021). In our regular results, this effect is masked by the labor-intermediate substitution effect, which is strong enough to overwhelm the emissions reductions due to undoing the environmental bias in tariffs and to leads to an overall increases in production emissions.

Our analysis here shows the crucial role of labor-intermediate substitution in accounting for increases in production emissions. Our results naturally depend on the elasticity of substitution between labor and intermediate inputs, which is equal to one in the Cobb-Douglas baseline. As discussed in more detail above, the literature suggests that Cobb-Douglas is in the range of reasonable values for this elasticity. We also, however, consider a broader range of values consistent with the literature estimates and find a strong labor-intermediate effect for this plausible range. More generally though, our analysis clearly highlights the key role of this substitution in accounting for the emission effects of tariffs, a point not noted previously in the literature.

The labor-intermediate substitution effect that we emphasize here connects to the canonical scale, composition and technique decomposition. Table A.5 shows that in terms of this decomposition, the emissions increases due to tariff removal are especially due to the technique effect (0.76%), which even exceeds the scale effect (0.5%). This is consistent with the labor-intermediate substitution story since the substitution would lead to producing with more emissions per value added at the country-industry level. To emphasize this point

[24] In our specific model, where labor is the only factor of production, the gains from trade show up as an increase in real wages. An increase in real wages is not exactly the same as a reduction in the price of intermediates relative to wages – the former depends on consumer prices and the latter on intermediate prices – but they are closely connected in this model.

[25] For computational efficiency, we calculate emissions changes under the Leontief assumption by imposing the same wage changes, and counterfactual tariff and efficiency changes, as in the main counterfactual. This is somewhat in the spirit of modular trade impact (Head and Mayer 2014) or conditional general equilibrium (e.g., Yotov et al. (2016)) exercises. As part of our sensitivity analysis, we show that emissions calculated using this procedure are nearly identical to emissions changes in full general equilibrium Leontief scenario.

[26] We report full general equilibrium results under the Leontief assumption in Table (6). The changes in emissions are nearly identical to what we report here.

further, we report the Copeland and Taylor decomposition under the Leontief assumption. The technique effect is -0.49% in this case, which shows that the labor-intermediate substitution is primarily responsible for the positive technique effect from tariff removal.

Results from the Leontief version of the model are also helpful for understanding the drivers of the value chain lengthening effects that drive emissions from transportation. The length of an individual sector's value chain depends directly on the use of intermediate inputs relative to labor in that sector and all associated upstream sectors, as well as the sectoral and country composition of inputs to that sector (and all associated upstream sectors). Results from the Leontief version of the model will therefore isolate how compositional changes contribute to changes in the lengths of value chains. The Q/V effect falls from 2% to 1% with the Leontief assumption (Table A.5), which indicates that labor-intermediate substitution at the firm level is an important driver of changes in value chain lengths. However, the lengthening effect remains strong in the Leontief version because eliminating tariff escalation also induces shifts towards sectors with longer value chains.

While we noted in the foregoing analysis that CO_2 increases by more than global GDP in percentage terms, this does not directly tell us anything about welfare. Current tariffs reduce emissions, but they do so at a tremendous cost of about 550\$/tCO_2, which is high relative to many other policy options (Gillingham and Stock 2018). If we value the global CO_2 externality at 50 \$/tCO_2 – a central estimate from IWG (2016) that is often used in the literature – the CO_2 cost of moving to global free trade (\$30 billion) is about an order of magnitude smaller than the \$339 billion in income gains. Even if we value the global CO_2 externality at 200 \$/tCO_2, which is consistent with more recent estimates of the social cost of carbon (Daniel et al. 2019; Hänsel et al. 2020), the income gains of liberalization easily dominate the climate costs. We note, however, that the exact valuation of the externality from CO_2 is complicated by the relatively small probability of catastrophic outcomes due to climate change (Weitzman 2014).

To explore the regional heterogeneity in the impacts of tariffs, we report results from separately removing OECD and non-OECD country tariffs in the second and third columns of Table 2. It is clear that the large emissions increases due to the global tariff removal are especially connected to the non-OECD tariffs, whose removal increases emissions substantially more than the increase in global GDP in percentage terms. Since OECD tariffs are relatively low to begin with, their elimination has a more modest effect on output and production/consumption emissions. Despite these differences, the the Q/V channel still accounts for a substantial portion of the transportation emissions increase for both groups of countries, and this is mostly driven by value chain lengthening. The labor-intermediate channel remains the dominant reason for the production emissions increase, as we see from these emissions increases becoming negative in the Leontief case for both groups of countries.

The primary takeaways from our analysis of tariffs also apply when we consider tariffs and non-tariff barriers to trade (NTBs). In Table A.6 we report results for scenarios where we remove both tariffs and NTBs.[27] There are larger increases in production and transportation CO_2 in these cases, relative to our results for tariff removal in Table 2, due to the higher levels of baseline protection. However, the relative contributions of lengthening value chains and labor-intermediate substitution are broadly consistent with the results for tariffs alone, if not larger.

4.2 Transportation Efficiency Improvements

In this section we explore how transportation fuel efficiency improvements impact CO_2 emissions. In addition to reducing the emissions intensity of transportation services, transportation efficiency improvements would effectively be a reduction in natural barriers to trade. We model fuel efficiency improvements through changes in ϕ_{ij}^{ms}, so improvements in fuel efficiency will lead to proportional reductions in transportation costs. Our results, therefore, do not account for potentially endogenous trade costs (e.g., Brancaccio et al. (2020)) or that fuel efficiency improvements might be associated with reductions in service quality (e.g., transit times, reliability).

In the first column of results in Table 3, we report results for aspirational, yet still plausible, fuel efficiency improvements over a ten year period.[28] These efficiency improvements lead to a substantial drop in transportation emissions (324 MT) due to reductions in emissions per unit gross output (ET/Q). The percent reduction in emissions per unit gross output is substantially smaller (in magnitude) than the efficiency improvements themselves due to increases in the average weight and, especially, the average distance traveled by shipped goods (Table A.7). Moreover, there are substantial increases in production emissions (647.1 MT) that more than offset the reductions in emissions from transportation. The increase in production emissions, as with tariff reductions, is largely due to the labor-intermediate substitution effect. When this effect is shut down, the increase in production emissions drops from 2.29% to 1.07%. Unlike in the tariff reduction this effect

[27] We use ad-valorem equivalent non-technical non-tariff barriers to trade from The World Bank (2020), which are estimated from data for the years 2012 to 2016 using the procedures from Kee et al. (2009). This database covers 56% of the trade flows by value in our data. We assume NTBs are zero for all other trade flows and aggregate to our countries and sectors using simple averages. We model non-tariff barriers in the same way as tariffs (e.g., any rents from NTBs are collected by importer governments).

[28] We base our improvements for air (16%), sea (25%) and road (22%) modes on targets proposed by the International Air Transport Association (IATA), International Maritime Organization (IMO), and the U.S. Department of Energy (US DOE) respectively. IATA targeted 1.5% annual efficiency improvements between 2009 and 2020. IMO targets a 40% reduction in CO_2 intensity by 2030, but some of these reductions may come from lower carbon fuels. The lower end projections for efficiency improvements due to US DOE's Supertrucks II program is 2% per year. We allow rail efficiency to improve at historical trends (10%).

does not become negative, which indicates that the relationship between transportation costs and embodied carbon is somewhat weaker than the relationship between tariffs and embodied carbon.

While a reduction in transportation emissions was to be expected given the improvement in fuel efficiency, the value chain expansion effect could potentially offset this reduction in transportation emissions to some degree, even apart from any effect on production emissions. Just like tariff reductions, improvements in transportation efficiency reduce trade costs and should therefore expand the amount of shipping for the same value added. We see that this is the case to some extent, but the Q/V effect for efficiency improvements is much more tempered than for tariff reductions. There are two main reasons for these differential value chain effects. First, since fuel costs tend to be higher for goods with shorter value chains, efficiency improvements induce sectoral shifts towards goods with shorter value chains, which dampens lengthening effects due to expansions in the use of intermediate inputs. This compositional effect is clearly evident in the negative Q/V and lengthening effects we obtain when we eliminate labor-material substitution using the Leontief version of the model (Table A.7).[29] In contrast, tariffs tend to be lower on upstream goods due to tariff escalation, so sectoral shifts in response to tariff reductions will tend to lengthen value chains. Second, unlike tariffs, improvements in efficiency effectively free up resources that were previously going towards transportation. This effect would lead to a relatively proportionate increase in Q and V, which would mute the Q/V to some extent. Put differently, for a given reduction in trade costs, the increase in V due to a tariff reduction is second-order, resulting from the reduction in the deadweight loss of the tariff when redistributing from the private sector to the government. For a transportation improvement, the increase in V is first-order in the trade cost reduction on account of the direct increase in resources.

In comparing tariff reductions to efficiency improvements our analysis brings new insights to a broader literature that contrasts tariffs versus natural trade barriers (e.g., Felbermayr et al. (2015); Besedes and Cole (2017); Jiao and Wei (2020)). These previous papers have considered differences in terms of welfare outcomes, entry and exit behavior in models with firm heterogeneity as well as political economy. Our analysis highlights how tariffs and natural trade barriers can differentially impact value chains and therefore environmental outcomes, due to both fundamental differences in how these barriers affect output and systematic differences in the patterns of barriers.

In the final five columns of Table 3 we report results for a 10% improvement in fuel efficiency for all modes and then for each mode individually. The 10% improvement is

[29] The negative correlation between sectors' value chain lengths and transportation costs also explain the slightly negative consumption shares effect.

roughly consistent with applying historical annual growth rates for 10 years. Across all modes observed fuel economy has increased by about 1% annually in recent decades (ICF International 2009; Faber and Hoen 2015; Kharina and Rutherford 2015). The efficiency improvements across modes, highlight the importance of intermediate goods in determining climate outcomes. Efficiency improvements for modes that typically carry intermediate inputs tend to lead to the largest production emissions increases. For example, improvements in air efficiency are not associated with the same type of large increase in production emissions as efficiency improvements in sea transport, consistent with the fact that air transportation is more likely to be carrying consumer goods. In fact, the production emissions increases easily overwhelm the decline in transport emissions for sea transport, but not for air transport. These patterns illustrate the importance of input use patterns when considering the environmental consequences of transportation efficiency programs. Programs that reduce transportation costs for intermediate inputs tend to induce increases in production emissions that undermine, potentially fully, the direct emissions reductions due to efficiency improvements.

4.3 Tariff Reform Schemes

In this section we consider the effect of several partial liberalization schemes, which are prominent in the context of WTO negotiations, in order to assess how the form of liberalization impacts CO_2. Since potential liberalization schemes vary in terms of how they affect intermediate inputs, we expect labor-intermediate and value chain mechanisms we emphasize above to operate differently across schemes. For comparison, we evaluate the CO_2 implications of proportional and "fixed" tariff reductions – whereby all tariffs are reduced by the same percentage point up to a tariff rate of zero – and three stylized, but broadly realistic, reform schemes.

The reform schemes we consider are a "Swiss Formula" approach and schemes that reduce "tariff peaks" and "tariff escalation".[30] 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 A. It is therefore a scheme that simultaneously harmonizes and reduces tariffs. We apply the Swiss Formula globally (i.e. on all sector by country-pair tariff rates).

[30] 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.

The tariff peak reduction approach lowers particularly high tariffs, which was a major theme during the Doha Round of WTO negotiations. We implement reductions in tariff peaks by imposing a global maximum tariff rate (e.g., $\tau' = \min(\tau, \tau^{max})$, where τ^{max} is the maximum tariff rate).[31] 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.

The motivation for reducing escalation is typically to increase market access for processed goods from developing countries, but reducing escalation may also work to correct the environmental bias in tariffs. We mimic an escalation reduction approach in our aggregate data by imposing a maximum tariff rate on downstream sectors but not upstream sectors.[32] For each importer, the maximum tariff rate for downstream sectors is $\tau^{max}_{down} = \bar{\tau}_{up} * B$, where $\bar{\tau}_{up}$ is the value weighted mean tariff on upstream sectors and $B >= 1$ is a scalar. This formulation prevents tariffs on downstream sectors from being lowered below average upstream tariff levels.

4.3.1 Comparing Liberalization Schemes

Figure 1 shows how emissions change under each scheme as we allow for a larger increase in global real income.[33] We report CO_2 outcomes for each scheme up to free trade, at which point the policies are equivalent, except for the escalation reduction case, which can only attain real income gains of up to 0.35%. Additional results for each counterfactual are reported in Table 4. The figure shows clearly that policies attaining the same real income gain can lead to markedly different CO_2 outcomes. Up through the real income gains from complete liberalization, proportional tariff reductions generate much less CO_2 than fixed reductions while the partial liberalization schemes generate considerably less CO_2 than proportional reductions (panel (a)). These differences are economically important. For a 0.25% increase in real income, fixed cuts in tariffs increase CO_2 by 1.5% while the reform schemes would increase CO_2 by less than 0.2%. At typical valuations, these differences in the value of CO_2 damages are roughly $25 billion (Table 4).

The CO_2 outcomes of the reform schemes – except for the escalation reduction, which cannot achieve real income gains this large – easily dominate fixed and proportional

[31]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).

[32]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.

[33]The policy parameters (proportional or fixed cuts, A, τ^{max} and B) for the scenarios we analyze here are not directly comparable. To ease comparisons across schemes, we therefore set up the model to search for the policy parameter values that achieve a targeted real income gain. We report the policy parameters used to obtain the targeted real income gain in Table 4.

reductions even at real income gains of 0.475%. This means that the reform schemes can lead to substantially depressed increases in CO_2 for all but the last 0.025% of attainable global income increases.

The differences between the Swiss Formula, peak reduction and escalation reduction are relatively small, and depend on the level of real income change under consideration. Escalation reduction generates the lowest increases up through real income increases of 0.275%, which is close to the maximum gains of this scheme as we have defined it. For additional real income gains, the CO_2 increases from escalation reduction grow rapidly and eventually overtake those from the Swiss Formula and peaks reduction. In this range, CO_2 changes from production/consumption and transport grow quickly and production/consumption CO_2 changes become positive.

The decompositions reported in Table 4 shed more light on the differences between the reform schemes vs. the fixed and proportional reductions. On the production side, we see the key role of the labor-intermediate channel here. Both the proportional and fixed reductions would lead to much smaller emissions increases if the labor-intermediate substitution channel were shut down. By contrast, the effect of shutting down this channel is more modest for the three reform schemes, as we can see from the much smaller difference between the actual production emissions change and the change under the fixed L-M scenario for these schemes. This pattern is apparent for real income gains of both 0.25% (panel (a)) and 0.35% (panel (b)).

The the weaker increases in transportation emissions for the reform cases reflect primarily the lower ET/Q effect. This effect is very large for the proportional and fixed reduction but quite small for the reform schemes and in fact negative for the tariff peaks reduction. This pattern is consistent with the fact that tariffs are highest on relatively lighter goods that incur less transportation expenses. Schemes that reduce the highest tariffs therefore especially reduce transportation emissions through this channel. We should note that with the exception of the fixed tariff reduction, the Q/V effect does not vary much across the different policies, ultimately because each of them, to some degree, reduces the highest tariffs most.

From Table 4, we also see that the average tariff reduction required for this level of welfare increase is much smaller for the special reform schemes. In some sense, these reform schemes generate relatively modest CO_2 increases because by cutting the highest tariff rates, they are able to generate substantial deadweight loss reductions – and therefore real income increases – even with a modest average tariff rate reduction. The lower average tariff rate reductions mean that the real income gains are attained with smaller increases in trade, tempering the increases in both transportation and production/consumption emissions.

In Table A.9, we compare the trade liberalization schemes when each scheme is calibrated to reduce the average tariff rate, weighted by baseline trade flows, by 50%.We now see that the production/consumption and transportation emissions increases from a proportional reduction is broadly comparable to the three reform schemes. However, the reform schemes deliver much larger increases in global GDP.

4.4 Mean Preserving Harmonization

We now expand our analysis beyond liberalization to see how the mechanisms we emphasize play out in reform scenarios that include tariff increases. A logical starting point is to analyze tariff harmonization, which is emphasized in Shapiro (2021) due to its ability to generate carbon-negative increases in output. In Table 5 we display results for a within-country harmonization of tariffs, where the weighted average average tariff in each country is kept constant. Like Shapiro (2021), such a harmonization increases output (0.43%) but reduces CO_2 (0.26%), though we obtain smaller reductions in emissions due to the weaker environmental bias in our data.

Although the emissions reductions from harmonization are largely the result of undoing the negative environmental bias in tariffs, the mechanisms we emphasize also play an important role. Harmonization actually increases transportation emissions due to the lengthening of value chains.[34] However, this effect is moderated by a negative ET/Q effect since this harmonization on average increases tariffs on heavier products. On the production side, we see that in contrast to the tariff reductions considered in the previous section, this mean-preserving harmonization gives us a somewhat *negative* labor-intermediate effect, as evidenced by the fact that emissions would have dropped somewhat more (-0.66% vs. -0.43%) if labor-intermediate substitution were switched off. This seems to be a result of the relatively strong increases in tariffs on intermediate inputs, which raises the price of materials relative to labor, and the strong reductions in tariffs on downstream goods, which induces a rise in the average real wage.

To better isolate the channels of adjustment underlying the harmonization 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 5). 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 ($16.7 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. Columns 2 and 3 also shed light on the source

[34] Both of these effects are hidden in Shapiro (2021), which does not separate production/consumption and transportation CO_2.

of the transportation emissions effects in Column 1. We see that value chain lengthening effect, which increases emissions is driven specifically by the tariff reductions whereas the moderating ET/Q reductions are driven by the tariff increases. The latter is again consistent with the fact the tariff increases are applying disproportionately to heavier goods.

Breaking down the harmonization into tariff increases and decreases shows that the CO_2 reductions from harmonization are dependent on tariff increases. The reductions in above average tariffs alone actually increases emissions, while the tariff increases alone lower emissions by 0.98%. 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 lost real income due to the tariff increases are of the same magnitude as the reduced external CO_2 costs at standard valuations. In other words, the implied mitigation cost of these tariff increases is roughly 50 $\$/tCO_2$. Moreover, the increase in global welfare taking into account the CO_2 externality is greatest for the tariff reductions alone ($302 billion relative to $291 billion for the mean preserving harmonization and less than $1 billion for the tariff increases).

The last column of Table 5 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 real income, it is possible to combine harmonization with substantial tariff increases while still keeping global real income fixed. Large emissions reductions of about 3.4% can be attained in this case. This is in substantial part due to the decrease in transportation emissions, though production/consumption emissions also decrease significantly. 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 also applies here: the implicit mitigation costs (almost $300 billion) of the required tariff increases exceeds the resulting reductions in CO_2 damages (roughly $60-$235 billion).

Given that the emissions reductions due to harmonization are exclusively due to tariff increases, it is reasonable to ask whether tariff liberalization alone can generate emissions reductions. To explore this question, we search numerically for the tariff rate *reductions* that minimize CO_2 subject to the equilibrium conditions, which is a procedure in the spirit of Ossa (2014).[35] Overall, we find that highly targeted tariff liberalization can indeed reduce emissions, but the achieved reductions are very small (Tables A.10 and A.11). If proportional reductions in tariffs are imposed within sectors but uniformly across countries, it is essentially

[35]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 (e.g., by sector).

impossible for liberalization to reduce CO_2. When the sectoral tariff reductions are allowed to differ by OECD and non-OECD countries, liberalization can reduce CO_2 levels by a modest 0.06% (second column of numbers in Table A.11). Outcomes are similar when we further allow sectoral tariff reductions to vary separately for the US. In each of these cases, production emissions due to sectoral reallocation are muted by labor-material substitution, lengthening value chains, and increases in the emissions intensity of transport.

4.5 Sensitivity Analysis

We now consider several sensitivity analyses, both as a way of assessing the robustness of our key results and in order to explore further the underlying mechanisms that we discuss throughout the paper. We focus on our baseline counterfactuals as well as on the partial liberalization schemes, which illustrate the various channels relating tariffs to carbon emissions. Each panel in Table 6 reports results under different data and modeling assumptions for our main counterfactuals. The Swiss Formula, tariff peak reduction and escalation are calibrated to attain a 50% reduction in average tariff rates, so that these counterfactuals attain, roughly, the same real income gains as the tariff removal and the efficiency improvement counterfactuals. The first row in each panel displays results under our central assumptions.

In our foregoing analysis, in order to highlight the effects of labor-intermediate substitution, we have used a Leontief version of the model where the labor-intermediate substitution is effectively shut off. For computational reasons, we did this exercise using same the income changes as our regular analysis. The second row of each panel in Table 6 considers the full general equilibrium Leontief model. These results are almost identical to our more partial Leontief results reported for the central assumptions (and in our previous tables). The percentage change in production emissions with L-M fixed is very close to the percentage change in production emissions from the full model with the Leontief assumption imposed.

The labor-intermediate substitution elasticity is clearly important in determining the effect of removing trade barriers on emissions. While, we noted earlier that $\sigma_L = 1$ implicit in the Cobb-Douglas specification is within the range of reasonable estimates from the literature, we also consider $\sigma_L = 0.5$ and $\sigma_L = 1.5$ (rows 3 and 4, respectively). Focusing on the tariff removal results, we see clearly how a higher elasticity magnifies the emissions from both production and transportation, with an especially strong effect for production emissions. The increases in Q/V as this elasticity is increased are due to the lengthening of value chains, as expected. We see a similar pattern in the case of efficiency improvements. Production emissions effects from the efficiency improvements are always fairly substantial and become more so as we increase the substitution elasticity. Notably, we begin to see value chain lengthening effects more significantly moderate the transportation emissions reductions when $\sigma_L = 1.5$.

The next rows report results under different assumptions regarding the trade elasticities. Results in the fifth row are generated using elasticities from Shapiro (2021) and are very similar to our central results, which use elasticities from the GTAP database. In the following 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 increase for all counterfactuals, mainly due to stronger scale and transportation effects. The stronger increases in transportation emissions under the tariff cases are driven by more pronounced lengthening effects. The compositional changes towards varieties with longer value chains induced by tariffs get amplified with larger trade elasticities. The amplified lengthening effect also occurs in the transportation efficiency counterfactual, but in this case the larger trade elasticities also significantly erode improvements in the average emissions intensity of shipping (ET/Q) induced by efficiency improvements due to stronger increases in the average distance traveled per unit of good shipped.

In the final two rows we report results under alternative assumptions regarding the transportation sector. In the "Iceberg Transport" row we account for transportation expenditures as an iceberg cost and account for transportation emissions using fixed emissions factors, which is consistent with the modeling in Shapiro (2016).[36] Changes in production emissions under these assumptions and our main assumptions are very similar. Changes in transportation emissions are slightly stronger with endogenous fuel price for transportation because reducing tariffs tends to lower the price of fuels.

The comparison between our baseline endogenous fuel price results and these exogenous iceberg fuel results are also indirectly informative about the consequences of imperfect pass-through of fuel prices into transportation costs, perhaps due to imperfect competition in the transportation sector. In our baseline results, fuel prices are fully passed through to transportation costs whereas in the iceberg case, changes in fuel prices do not affect transportation costs. Given that these two diametrically opposed assumptions give us very similar results, the pass-through margin is unlikely to be a significant driver of our findings.

Finally, we use transportation fuel expenditure factors ϕ_{ij}^{sm} that are consistent with fuel use per kg-km by transportation mode, x_k, from the high scenario in Cristea et al. (2013) and those used by Shapiro (2016). The main difference from our central fuel use factors is that the fuel use from air transport are 80% higher, which slightly amplifies changes in

[36]The efficiency improvement counterfactuals are not compatible with how we implement the "Iceberg Transport" costs, so we do not report that case.

transportation emissions.

5 Additional Counterfactuals

5.1 2018 Trade War

The foregoing analysis sheds light on the effect of trade barriers by considering hypothetical policy changes such as global tariff liberalization. It would also be informative to more directly examine a real tariff change that would be substantial enough in magnitude to have a measurable effect on CO_2 emissions. The 2018 trade war – primarily between the US and China but also involving other US trading partners to a lesser extent – provides a unique example of such a policy change and also complements our earlier analysis by considering a tariff increase rather than a decrease. We evaluate the impacts of this trade war using data from Amiti et al. (2019), who compile US import tariffs and retaliatory tariffs on US exports for 2017 and 2018 from a variety of national data sources. For our trade war scenarios we calculate the additional tariff rates due to the trade war at the end of 2018 (Table A.12) and apply these level changes to our baseline tariff rates.[37]

The results for these scenarios are reported in Table 7. The first column reports the combined effect of US and retaliatory tariffs. As expected, we see a decrease in global output as well as a decrease in both production and transportation emissions. The emissions fall by substantially more in percent terms than global output. The table also shows that the decrease in production emissions is primarily through the labor-intermediate substitution channel: the decrease drops from 0.17% to 0.03% when this channel is shut down. Both the Q/V and ET/Q effects contribute to the decrease in transportation emissions, with the ET/Q being dominant.

The second two columns help break down the combined results by considering separately counterfactual scenarios where the US tariffs are imposed without retaliation and, somewhat artificially, where the retaliatory tariffs are imposed without US tariffs. These results show that US tariffs primarily affect production vs. transportation emissions whereas the opposite is true for China's retaliatory tariffs. For both sets of tariffs, the labor-intermediate effect is dominant in explaining the decrease in production emissions. For transportation emissions, we see an especially large ET/Q effect in the case of Chinese tariffs. Decomposing these effects (in unreported results) suggests that the Chinese tariffs largely induce changes in the sourcing of goods with associated increases in average distance, while the US tariffs induced a shift to more domestic transport, which tends to be shorter but more emissions intensive. The reduction in transportation emissions through the Q/V effect is driven primarily by

[37] The retaliatory tariffs are those imposed by China, Canada, Russia, Mexico, Turkey, the EU and India. We aggregate these tariff rates from detailed industries (HTS6 and HTS10) to our GTAP sectors using the 2017 total value of imports/exports from the U.S. Census Bureau.

shifts in consumption towards goods with shorter value chains in the case of US tariffs and by shortening of value chains for the retaliatory tariffs.

While our focus in this paper is on the general relationship between trade policy and CO_2 emissions and not specifically on evaluating the 2018 trade war, it is instructive to compare our results to some related papers on this topic. Our CO_2 and income changes are quite similar to those from a number of studies using GTAP (Lin et al. 2019; Lu et al. 2020). The welfare effects under our model in the overall trade war scenario are also broadly in line – though somewhat more muted – with Amiti et al. (2019) and Fajgelbaum et al. (2020), though the effect of unilateral US tariffs is quite different.[38]

Overall, these results especially highlight the rich set of mechanisms through which tariffs can affect emissions patterns. Not only are there differences between transportation vs. production emissions, but the channels through which these operate can be quite different. The most consistent result here and in the previous section seems to be the clear role of the labor-intermediate effect in accounting for changes in production emissions.

5.2 Carbon Tariffs

While our focus in this paper is on ordinary "non-carbon" tariffs rather than hypothetical climate related trade policy – on which there is a substantial literature – in this section we illustrate how the channels we document would play a role in the emissions effects due to these policies as well. We explore this point by considering a series of hypothetical climate policies. First, we impose a uniform global carbon tariff of \$50 on the baseline CO_2 embodied in traded goods (first column of Table 8).[39] We note that this counterfactual is distinct from typical carbon tariff proposals, which would be paired with sub-global climate policy, but should operate through some of the same underlying channels.

We see from the first column that such a policy would substantially decrease production and transportation emissions. The labor-intermediate channel again plays a remarkably large role in accounting for the production emissions decrease: when this channel is shut down, the emissions decrease is 0.90% rather than 2.91%. The important role of this channel here is notable given that tariffs on embodied emissions are specifically designed to induce a favorable reallocation from more polluting to less polluting goods. This suggests that the

[38] These papers find complete pass through of US tariffs into consumer prices, which leads to larger welfare losses for the US, whereas in our model, unilateral tariffs would actually lead to a modest improvement in welfare due to terms-of-trade effects. Fajgelbaum et al. (2020) note that the complete pass-through of 2018 tariffs they find is in contrast to the relatively common finding of incomplete pass-through in the context of other tariffs studied in the literature. They suggest that a possible reason for this difference is that the 2018 tariff estimates are short-term effects of tariffs that may not be permanent. In our model, the results should be interpreted as longer-term effects when the tariffs would be permanently in place.

[39] We calculate embodied CO_2 for each X_{ij}^s as the embodied emissions from producing s in i, including the transport of inputs, plus emissions from transportation of s from i to j. Carbon tariffs of this form are analyzed in more detail in Bohringer et al. (2018).

labor-material substitution should be a key consideration when thinking about the effect of hypothetical carbon tariffs. On the transportation emissions front, the Q/V and ET/Q channels both play a substantial role, with the ET/Q effect unsurprisingly being especially large. The Q/V effect is primarily due to the shortening of value chains that such a policy would bring about by raising the costs of importing carbon intensive intermediate goods.

The next column report results for a 50 $/t$CO_2$ tariff on international transportation emissions. This tariff can be thought of as a special type of carbon tariff, but is a more natural standalone policy than carbon tariffs. These results are on the whole fairly consistent with the first column, though with somewhat more modest magnitudes. In the final column, we show similar results for a global tax on transportation CO_2 – that is we apply the a 50 $/t$CO_2$ tax on domestic and international transport emissions.

These results relate to Mundaca et al. (2021), who examine the impact of carbon taxes on maritime transport on the emissions from maritime transport. Our analysis here highlights the importance of accounting for production as well as transportation emissions even in the context of taxes or other policies that target transportation, particularly if the policies affect the shipping of intermediate inputs. From the second and third column of 8, we see that the decrease in production CO_2 is comparable or even larger than the decrease in transportation emissions, largely due to labor-material substitution. This echoes (somewhat in reverse) our findings in the context of transportation efficiency improvements in the previous section, where the increase in production emissions was comparable to the decrease in transportation emissions.

5.3 Broader Considerations

Our analysis of current and hypothetical tariffs has especially highlighted the role of intermediate input use and transportation in accounting for global emissions changes. These results reflect the fact that tariffs are in part a tax on intermediate inputs. To the extent this is the case, we should expect that other types of policies that directly or indirectly tax intermediate inputs would also have qualitatively comparable impacts. We illustrate this point in Table 9 by showing the effects of two hypothetical policies that tax intermediate inputs more broadly. The first column shows the effects of a global tax on the sectors we classify as upstream. The second column considers the effects of a turnover tax, which is an indirect tax on gross sales that applies at each stage in production.

Both policies generate strong reductions in transportation and production emissions. Consistent with what we found for tariffs, a substantial potion of the reduction in transportation emissions is due to the Q/V effect. This shortening of value chains is especially pronounced in the case of the turnover tax, where the Q/V effect actually exceeds the ET/Q effect. This is remarkable since this policy directly taxes fuel for transportation, which contributes to a strong ET/Q effect. For production emissions, the role of the labor-intermediate channel is even more stark, with the very large emissions reductions becoming much more modest when this channel is switched off.

For our purposes, the primary reason to evaluate this set of hypothetical policies is to shed further light on the mechanisms through which tariffs and other trade barriers affect CO_2. These results are, however, also informative about other indirect taxes. For example, sales taxes in the United States do function in part 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). Hence, in thinking about the CO_2 impacts of tax systems more broadly (c.f. National Research Council (2013)) it is important to think about the extent to which these systems tax intermediate inputs.

6 Conclusion

We study the CO_2 impacts of changes in trade barriers– through changes in tariffs and the fuel efficiency of transportation – using a quantitative general equilibrium model. We find that changes in the use and transportation of intermediate inputs play a critical role determining the emissions consequences of changes in trade barriers. Reductions in trade barriers increase gross output relative to value added, indicating a lengthening of value chains, which leads to a strong increase in transportation emissions because these emissions depend directly on the gross flow of goods. Reductions in trade barriers also increases wages relative to the price of other goods, which increases the quantity of intermediates relative to labor used in production and, therefore, emissions per value added. We also consider the emissions impacts of 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 use and transportation of intermediates in understanding the CO_2 impacts of existing trade barriers, the mechanisms we emphasize are likely to be important in a wide range of other contexts as well. For example, we demonstrate that labor-material substitution and value chain expansion 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 impacts on intermediate goods. Since other forms of indirect taxes are also likely to function as taxes on intermediates 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 other global policies and trends are likely to affect the incentives to use intermediates relative to labor, and therefore affect emissions too through the mechanisms we emphasize. Beyond CO_2, the labor-intermediate mechanism in particular could also play an important role in linking non-environmental policies to other production externalities, like local air and water pollution, since these will also tend to increase with increased use of intermediates.

A caveat to our analysis is that, like all existing analyses of trade barriers on GHGs (Pothen and Hübler 2018; Shapiro 2021), we do not capture all sources of emissions. In particular we capture only CO_2 related to fossil fuel use, and not CO_2 related to land use change and non-CO_2 GHGs from industrial processes and agriculture. Although including these sources may amplify some of the emissions changes we observe, it is unlikely to alter our primary findings since these sources of emissions would also be moderated, to some extent, by substitution away from intermediate inputs. That said, analyzing the extent to which trade barriers impact other sources of emissions is an important area for future research, especially given the sensitivity of agriculture in the context of trade policies and agreements.

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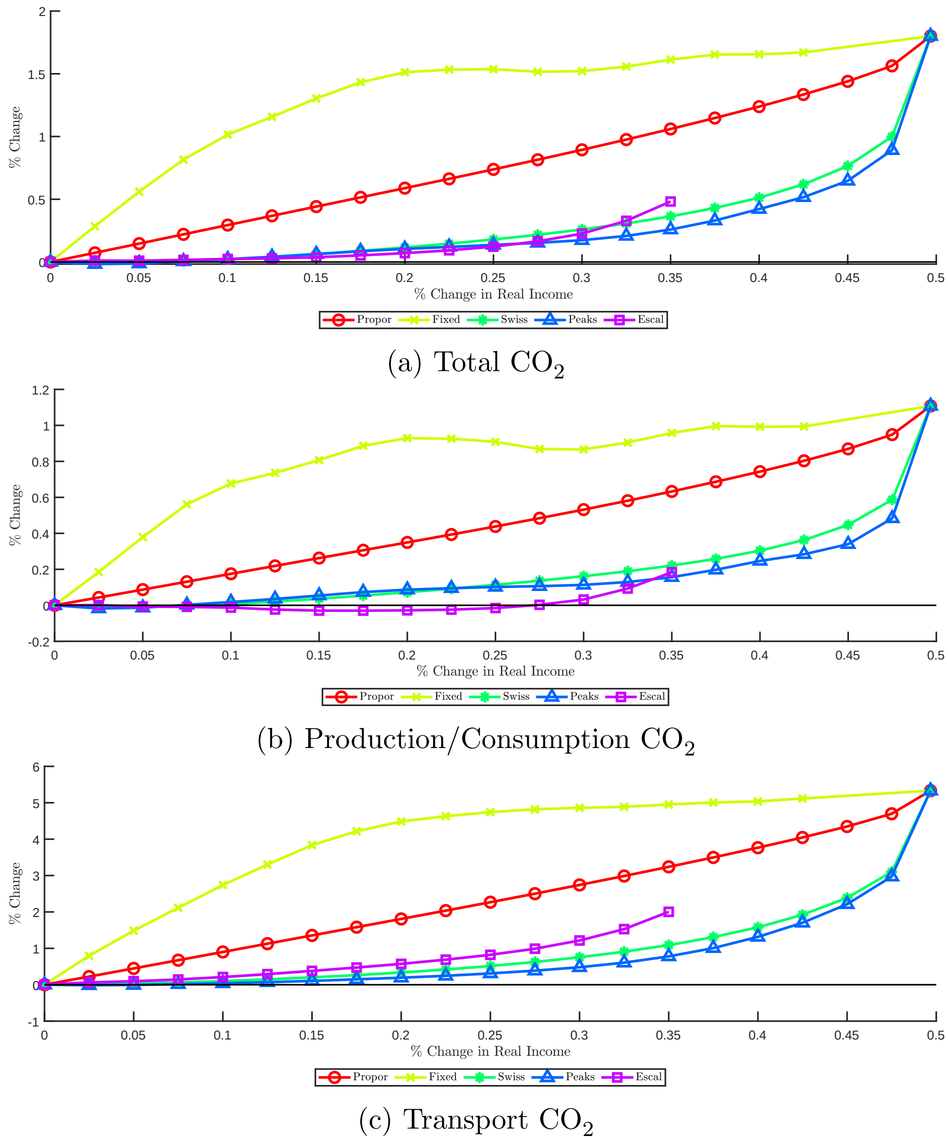

(a) Total CO_2

(b) Production/Consumption CO_2

(c) Transport CO_2

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

Figure 1: Comparing Liberalization Scenarios at Fixed Income Increases

	ϵ_s	Value (billion \$)	Int. Share	$\tilde{Q}$	CO_2 (MT)			
					Used	Using	Transport	Embodied
Agriculture	4.87	5088.18	0.40	1.90	0.00	423.23	455.83	814.23
Chemical products	6.60	7795.54	0.69	2.66	0.00	997.21	522.18	923.83
Coal	6.10	516.89	0.38	2.37	13688.94	220.51	178.07	295.95
Electricity	5.60	2698.44	0.61	2.31	0.00	14264.35	0.00	3703.23
Equipment	6.37	5183.53	0.74	3.05	0.00	63.49	180.96	1680.34
Food	5.08	7208.90	0.70	2.58	0.00	302.96	413.60	2223.99
Machinery nec	8.10	7397.29	0.66	2.85	0.00	136.47	552.20	2401.99
Electronic equipment	8.80	3570.12	0.74	3.15	0.00	42.08	301.09	883.20
Manufactures nec	7.50	1438.38	0.62	2.59	0.00	63.68	37.56	444.41
Metal products	7.38	7272.93	0.70	2.79	0.00	1317.48	715.50	412.20
Mineral products	5.80	2078.57	0.63	2.43	0.00	1394.50	215.66	143.81
Minerals	1.80	1310.79	0.45	2.32	0.00	191.57	504.27	23.67
Natural Gas	31.48	862.71	0.34	1.89	6515.76	465.85	154.41	1087.52
Oil	10.40	3562.48	0.21	1.63	207.38	335.11	419.38	0.07
Other	3.80	73972.28	0.40	1.88	0.00	1271.65	0.00	11950.89
Paper products	5.90	2515.97	0.60	2.44	0.00	204.58	329.49	277.43
Passenger transport	3.80	1986.19	0.64	2.50	0.00	1784.91	0.00	2573.31
Petroleum products	4.20	5701.18	0.86	2.59	13764.77	1109.92	390.64	3252.27
Textiles	7.59	3283.06	0.71	2.83	0.00	99.04	120.59	943.10
Wood products	6.80	1210.79	0.65	2.57	0.00	40.52	110.64	141.40
Transport	-	-	-	-	-	5602.08	-	-
Households	-	-	-	-	-	3845.64	-	-

Notes: $\tilde{Q}$ is the consumption weighted average value chain length by sector. “Transport” row reflects fuel used for transport of goods and “Households” row captures fossil fuels consumed directly by households. Emissions are the only relevant statistics for these rows. The passenger transportation (“Pass Transport”) sector reflects transportation services purchased by households.

Table 1: Summary Statistics by Sector

	Proport.	OECD	Non-OECD
Δ CO_2 (MT)	615.3	135.8	468.0
Product/Consump	316.6	37.1	274.1
Transport	298.7	98.7	193.8
OECD	298.3	106.8	187.0
non-OECD	317.0	29.0	281.0
Δ CO_2 (%)	1.80	0.40	1.37
Δ Transport CO_2 per $ Value Added (%)	4.81	1.56	3.14
Q/V	1.99	0.58	1.29
shares	0.13	0.11	0.03
lengthening	1.84	0.46	1.26
ET/Q	2.76	0.98	1.82
Δ Production CO_2 (%)	1.22	0.16	1.03
L-M Fixed	-0.51	-0.26	-0.26
EV (% of GDP)	0.50	0.19	0.31
EV (billion $)	338.8	132.9	212.1
OECD	187.6	51.9	136.2
non-OECD	151.2	81.0	75.9
CO_2 Damage @ SCC=50 $/t (billion $)	30.77	6.79	23.40
CO_2 Damage @ SCC=200 $/t (billion $)	123.06	27.16	93.59
Change in Avg. Tariff Rate	-2.40	-0.80	-1.60

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 2: Decomposition of Impacts of Removing Global Tariffs

	Projected	All Modes	Sea	Air	Road	Rail
Δ CO_2 (MT)	322.8	-14.1	58.5	-50.8	-21.9	2.7
Product/Consump	647.1	299.5	137.4	5.0	139.6	15.9
Transport	-324.3	-313.6	-78.9	-55.8	-161.5	-13.3
Δ CO_2 (%)	0.94	-0.04	0.17	-0.15	-0.06	0.01
Δ Transport CO_2 per $ Value Added (%)	-6.24	-5.87	-1.49	-1.08	-2.99	-0.25
Q/V	0.20	0.04	0.03	-0.00	0.00	0.00
shares	-0.02	-0.01	0.01	-0.02	-0.01	-0.00
lengthening	0.22	0.05	0.03	0.01	0.01	0.00
ET/Q	-6.43	-5.90	-1.52	-1.08	-3.00	-0.25
Δ Production CO_2 (%)	2.29	1.06	0.49	0.01	0.50	0.06
L-M Fixed	1.07	0.40	0.24	-0.09	0.21	0.03
EV (% of GDP)	0.48	0.29	0.08	0.08	0.11	0.01
EV (billion $)	329.3	194.4	56.3	55.1	77.1	5.8
CO_2 Damage @ SCC=50 $/t (billion $)	16.14	-0.71	2.93	-2.54	-1.10	0.13
CO_2 Damage @ SCC=200 $/t (billion $)	64.57	-2.83	11.70	-10.16	-4.39	0.53
Change in Avg. Tariff Rate	0.00	0.00	0.00	0.00	0.00	0.00

Notes: First column reports impacts of plausible mode-specific improvements in fuel efficiency over ten years (16% for air; 22% for road; 10% for rail; 25% for sea). The remaining columns report impacts of a 10% improvement in transportation fuel efficiency (with associated fuel cost reductions), first to all modes then to each mode individually.

Table 3: Decomposition of Impacts of Transportation Efficiency Improvements

	Proport.	Fixed	Swiss	Peaks	Escalation
Δ CO_2 (MT)	252.2	525.2	61.3	46.6	41.7
Product/Consump	125.2	259.6	32.5	29.2	-4.4
Transport	127.0	265.6	28.8	17.4	46.1
Δ CO_2 (%)	0.74	1.54	0.18	0.14	0.12
Δ Transport CO_2 per \$ Value Added (%)	2.01	4.48	0.26	0.06	0.57
Q/V	0.40	0.98	0.26	0.41	0.36
shares	0.06	0.11	0.02	0.01	0.06
lengthening	0.34	0.86	0.24	0.40	0.30
ET/Q	1.60	3.47	0.01	-0.35	0.21
Δ Production CO_2 (%)	0.45	0.99	0.10	0.10	-0.02
L-M Fixed	-0.27	-0.40	-0.16	-0.13	-0.22
EV (% of GDP)	0.25	0.25	0.25	0.25	0.25
EV (billion \$)	170.5	170.5	170.5	170.5	170.5
CO_2 Damage @ SCC=50 \$/t (billion \$)	12.61	26.26	3.07	2.33	2.08
CO_2 Damage @ SCC=200 \$/t (billion \$)	50.44	105.05	12.26	9.31	8.34
Policy Parameter	0.54	0.56	0.98	0.40	7.07
Change in Avg. Tariff Rate	-1.30	-2.31	-0.33	-0.12	-0.48

(a) Change in Real Income = 0.25%

	Proport.	Fixed	Swiss	Peaks	Escalation
Δ CO_2 (MT)	362.3	551.2	124.1	88.3	164.7
Product/Consump	180.8	273.7	63.1	44.7	52.5
Transport	181.4	277.4	61.0	43.6	112.2
Δ CO_2 (%)	1.06	1.61	0.36	0.26	0.48
Δ Transport CO_2 per \$ Value Added (%)	2.88	4.59	0.74	0.43	1.65
Q/V	0.67	1.21	0.56	0.69	0.77
shares	0.08	0.12	0.04	0.03	0.09
lengthening	0.58	1.08	0.53	0.66	0.67
ET/Q	2.20	3.33	0.17	-0.26	0.87
Δ Production CO_2 (%)	0.66	1.05	0.22	0.16	0.22
L-M Fixed	-0.36	-0.39	-0.24	-0.19	-0.24
EV (% of GDP)	0.35	0.35	0.35	0.35	0.35
EV (billion \$)	238.7	238.7	238.7	238.7	238.7
CO_2 Damage @ SCC=50 \$/t (billion \$)	18.11	27.56	6.21	4.42	8.23
CO_2 Damage @ SCC=200 \$/t (billion \$)	72.45	110.23	24.82	17.67	32.94
Policy Parameter	0.73	1.88	0.39	0.16	1.47
Change in Avg. Tariff Rate	-1.74	-2.38	-0.61	-0.34	-1.04

(b) Change in Real Income = 0.35%

Notes: Columns reflect each liberalization scenario when the policy parameter (proportional or fixed cuts, A, τ^{max} and B) is set to achieve a target change in real income. The "Policy Parameter" row reports the specific value required to achieve the targeted real income gain.

Table 4: Comparing Liberalization Scenarios at Target Real Income

	Harmonization	Reduction Only	Increase Only	Fixed Real Inc
Δ CO_2 (MT)	-88.3	251.2	-338.2	-1175.2
Product/Consump	-124.2	105.6	-227.9	-793.2
Transport	35.9	145.6	-110.3	-382.0
Δ CO_2 (%)	-0.26	0.73	-0.99	-3.44
Δ Transport CO_2 per \$ Value Added (%)	0.21	2.13	-1.94	-6.82
Q/V	0.85	1.21	-0.35	-0.58
shares	0.08	0.10	-0.01	-0.02
lengthening	0.76	1.11	-0.34	-0.56
ET/Q	-0.64	0.90	-1.60	-6.28
Δ Production CO_2 (%)	-0.43	0.41	-0.83	-2.85
L-M Fixed	-0.66	-0.43	-0.24	-0.61
EV (% of GDP)	0.43	0.46	-0.02	0.00
EV (billion \$)	296.2	314.7	-16.7	0.0
CO_2 Damage @ SCC=50 \$/t (billion \$)	-4.41	12.56	-16.91	-58.76
CO_2 Damage @ SCC=200 \$/t (billion \$)	-17.66	50.23	-67.65	-235.05
Change in Avg. Tariff Rate	-0.00	-1.24	1.24	5.37

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 5: Decomposition of Impacts of Mean Preserving Harmonization

			Transport CO_2						Production CO_2		
	EV (%)	Δ CO_2 (MT)	Δ (MT)	Δ (%)	Q/V	shares	length	ET/Q	Δ (MT)	Δ (%)	L-M Fixed
Central	0.506	607.328	292.129	5.215	2.015	0.126	1.867	2.617	302.510	1.223	-0.529
σ_L=0.0	0.469	110.889	229.050	4.089	1.004	0.123	0.870	2.573	-132.719	-0.537	-0.537
σ_L=0.5	0.487	353.844	259.988	4.641	1.497	0.125	1.356	2.598	80.277	0.325	-0.534
σ_L=1.5	0.525	871.857	325.447	5.809	2.559	0.128	2.402	2.631	534.523	2.162	-0.521
ϵ^s - Shapiro (2019)	0.507	604.642	313.285	5.592	1.944	0.121	1.802	3.056	281.623	1.139	-0.525
$\epsilon^s * 1.5$	0.992	1079.086	506.474	9.041	4.394	0.341	4.007	3.425	552.760	2.235	-0.378
$\epsilon^s * 0.66$	0.293	476.210	210.163	3.752	1.359	0.057	1.290	2.062	255.172	1.032	-0.474
Iceberg Transport	0.509	582.312	258.232	4.734	2.006	0.130	1.855	2.155	306.598	1.245	-0.527
High ϕ	0.505	747.084	438.530	6.200	2.034	0.127	1.884	3.560	297.819	1.201	-0.537

(a) Tariff Removal

			Transport CO_2						Production CO_2		
	EV (%)	Δ CO_2 (MT)	Δ (MT)	Δ (%)	Q/V	shares	length	ET/Q	Δ (MT)	Δ (%)	L-M Fixed
Central	0.483	322.835	-324.252	-5.788	0.203	-0.019	0.219	-6.430	565.141	2.285	1.071
σ_L=0.0	0.477	-24.694	-372.405	-6.648	-0.216	-0.021	-0.197	-6.890	263.847	1.067	1.067
σ_L=0.5	0.480	149.656	-348.286	-6.217	-0.006	-0.020	0.012	-6.659	415.073	1.678	1.069
σ_L=1.5	0.486	495.019	-300.286	-5.360	0.410	-0.019	0.425	-6.203	714.218	2.888	1.073
ϵ^s - Shapiro (2019)	0.478	2.172	-541.337	-9.663	0.069	-0.010	0.080	-10.155	479.399	1.939	0.828
$\epsilon^s * 1.5$	0.517	995.981	180.192	3.217	0.456	-0.006	0.447	2.220	716.106	2.896	1.571
$\epsilon^s * 0.66$	0.465	25.334	-573.420	-10.236	0.086	-0.023	0.109	-10.728	522.440	2.113	0.925
High ϕ	0.651	580.378	-211.764	-2.994	0.306	-0.025	0.326	-3.915	690.697	2.786	1.258

(b) Transportation Efficiency

			Transport CO_2						Production CO_2		
	EV (%)	Δ CO_2 (MT)	Δ (MT)	Δ (%)	Q/V	shares	length	ET/Q	Δ (MT)	Δ (%)	L-M Fixed
Central	0.451	263.425	134.736	2.405	1.107	0.077	1.026	0.830	117.987	0.477	-0.387
σ_L=0.0	0.419	22.771	104.564	1.867	0.561	0.075	0.491	0.876	-93.403	-0.378	-0.378
σ_L=0.5	0.435	139.938	119.354	2.131	0.826	0.076	0.751	0.856	9.454	0.038	-0.383
σ_L=1.5	0.468	393.644	150.698	2.690	1.403	0.078	1.317	0.797	232.616	0.941	-0.389
ϵ^s - Shapiro (2019)	0.452	257.105	147.621	2.635	1.042	0.080	0.959	1.120	100.672	0.407	-0.385
$\epsilon^s * 1.5$	0.888	564.492	256.293	4.575	2.530	0.217	2.323	1.096	286.894	1.160	-0.262
$\epsilon^s * 0.66$	0.259	184.924	94.422	1.685	0.707	0.034	0.669	0.711	83.483	0.338	-0.366
Iceberg Transport	0.454	254.759	118.300	2.169	1.116	0.079	1.036	0.584	122.839	0.499	-0.380
High ϕ	0.450	325.629	200.722	2.838	1.112	0.077	1.031	1.251	115.225	0.465	-0.392

(c) Swiss Formula

			Transport CO_2						Production CO_2		
	EV (%)	Δ CO_2 (MT)	Δ (MT)	Δ (%)	Q/V	shares	length	ET/Q	Δ (MT)	Δ (%)	L-M Fixed
Central	0.461	251.319	140.435	2.507	1.243	0.087	1.149	0.783	102.279	0.414	-0.458
σ_L=0.0	0.429	8.744	108.945	1.945	0.658	0.084	0.575	0.846	-109.833	-0.444	-0.444
σ_L=0.5	0.445	126.475	124.356	2.220	0.942	0.085	0.853	0.818	-6.974	-0.028	-0.452
σ_L=1.5	0.479	383.666	157.159	2.805	1.563	0.088	1.462	0.741	218.342	0.883	-0.462
ϵ^s - Shapiro (2019)	0.464	246.636	157.041	2.803	1.174	0.090	1.077	1.141	83.053	0.336	-0.461
$\epsilon^s * 1.5$	0.919	597.849	280.004	4.998	3.006	0.245	2.755	1.006	299.922	1.213	-0.312
$\epsilon^s * 0.66$	0.264	165.045	96.099	1.715	0.759	0.041	0.712	0.684	63.258	0.256	-0.436
Iceberg Transport	0.465	243.329	123.002	2.255	1.258	0.089	1.163	0.517	108.414	0.440	-0.446
High ϕ	0.461	315.239	208.443	2.947	1.247	0.087	1.152	1.212	99.295	0.400	-0.464

(d) Tariff Peaks

			Transport CO_2						Production CO_2		
	EV (%)	Δ CO_2 (MT)	Δ (MT)	Δ (%)	Q/V	shares	length	ET/Q	Δ (MT)	Δ (%)	L-M Fixed
Central	0.362	206.246	133.939	2.391	0.871	0.095	0.762	1.141	74.112	0.300	-0.249
σ_L=0.0	0.347	53.994	111.745	1.995	0.504	0.091	0.405	1.132	-57.165	-0.231	-0.231
σ_L=0.5	0.355	130.091	122.865	2.193	0.689	0.093	0.585	1.135	8.453	0.034	-0.241
σ_L=1.5	0.369	282.299	144.926	2.587	1.049	0.096	0.936	1.149	139.700	0.565	-0.256
ϵ^s - Shapiro (2019)	0.409	226.159	155.201	2.770	1.021	0.101	0.909	1.317	74.424	0.301	-0.290
$\epsilon^s * 1.5$	0.739	446.820	232.844	4.156	2.097	0.253	1.828	1.269	209.596	0.848	-0.054
$\epsilon^s * 0.66$	0.201	127.420	91.291	1.630	0.534	0.047	0.478	0.886	40.293	0.163	-0.298
Iceberg Transport	0.362	196.437	119.892	2.198	0.852	0.093	0.747	0.969	75.307	0.306	-0.246
High ϕ	0.362	274.029	203.150	2.872	0.882	0.095	0.773	1.605	73.839	0.298	-0.246

(e) Escalation

Notes: Efficiency results are for plausible mode-specific improvements in fuel efficiency over ten years (16% for air; 22% for road; 10% for rail; 25% for sea). All tariff reform policies implement to achieve a 50% reduction in average tariff rate, weighted by baseline trade flows.

Table 6: Main Results Using Alternative Data and Assumptions

	Combined	US	Retaliatory
Δ CO_2 (MT)	-70.3	-39.3	-32.9
Product/Consump	-43.0	-34.0	-9.7
Transport	-27.3	-5.3	-23.1
USA	-26.1	2.0	-29.5
China	-28.6	-21.8	-7.4
Other	-15.7	-19.5	4.1
Δ Transport CO_2 per $ Value Added (%)	-0.46	-0.08	-0.40
Q/V	-0.07	-0.04	-0.03
shares	-0.03	-0.05	0.01
lengthening	-0.04	0.00	-0.05
ET/Q	-0.39	-0.04	-0.37
Δ Production CO_2 (%)	-0.17	-0.14	-0.04
L-M Fixed	-0.03	-0.05	0.02
EV (% of GDP)	-0.03	-0.01	-0.01
EV (billion $)	-17.2	-8.1	-8.7
USA	-3.6	5.8	-9.4
China	-13.6	-14.1	0.3
Other	0.1	0.2	0.4
CO_2 Damage @ SCC=50 $/t (billion $)	-3.51	-1.96	-1.64
CO_2 Damage @ SCC=200 $/t (billion $)	-14.06	-7.86	-6.58
Change in Avg. Tariff Rate	0.28	0.17	0.12

Notes: The "Combined" column reports a counterfactual that adds the level changes in tariffs due to the US-China trade war, as of December 2018, to our baseline tariffs. The "US" and "Retaliatory" columns raise the US and retaliating countries tariffs separately.

Table 7: Impacts of 2018 Tariff Increases on CO_2

	Embodied CO2	Inter. Transport CO2	Transport CO2
Δ CO_2 (MT)	-1276.0	-349.2	-714.3
Product/Consump	-766.1	-134.3	-406.4
Transport	-509.9	-214.9	-308.0
Δ CO_2 (%)	-3.73	-1.02	-2.09
Δ Transport CO_2 per $ Value Added (%)	-8.86	-3.81	-5.47
Q/V	-1.11	-0.22	-0.48
shares	-0.17	0.01	0.02
lengthening	-0.94	-0.23	-0.50
ET/Q	-7.84	-3.60	-5.02
Δ Production CO_2 (%)	-2.91	-0.50	-1.56
L-M Fixed	-0.90	-0.17	-0.73
EV (% of GDP)	-0.26	-0.02	-0.02
EV (billion $)	-180.6	-16.7	-16.7
CO_2 Damage @ SCC=50 $/t (billion $)	-63.80	-17.46	-35.72
CO_2 Damage @ SCC=200 $/t (billion $)	-255.20	-69.84	-142.86
Change in Avg. Tariff Rate	4.17	0.58	0.58

Notes: Counterfactuals impose 50 $/t$CO_2$ carbon tariff on embodied emissions or emissions from transportation at the industry by origin level.

Table 8: Decomposition of Impacts of Carbon Tariffs

	Upstream	Turnover
Δ CO_2 (MT)	-2105.4	-2679.1
Product/Consump	-1786.4	-2257.4
Transport	-319.0	-421.7
Δ CO_2 (%)	-6.16	-7.84
Δ Transport CO_2 per \$ Value Added (%)	-5.62	-7.37
Q/V	-1.92	-3.95
shares	-0.03	-0.06
lengthening	-1.89	-3.90
ET/Q	-3.77	-3.56
Δ Production CO_2 (%)	-6.58	-9.00
L-M Fixed	-2.89	-1.57
EV (% of GDP)	-0.08	-0.17
EV (billion \$)	-54.3	-116.6
CO_2 Damage @ SCC=50 \$/t (billion \$)	-105.27	-133.96
CO_2 Damage @ SCC=200 \$/t (billion \$)	-421.07	-535.83
Change in Avg. Tariff Rate	1.32	3.00

Notes: Upstream tax imposes a fixed tax on each sector we define as upstream in the escalation reduction scheme. Turnover tax is implemented by adding a fixed value to all tariffs including those where $i = j$. In both cases tax is set at 0.03.

Table 9: Decomposition of Impacts of Other Policies

Supplemental Appendix for "Trade Barriers and CO_2"

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A Additional Data and Calculations

A.1 Weight-to-value and Mode Shares Data

The Cristea et al. (2013) data reports values for 27 GTAP sectors and 40 regions (28 individual countries and 12 aggregated regions) for the year 2004. We aggregate the 27 sectors to our 20 sectors using weighted averages. We apply the regional averages in the Cristea et al. (2013) to each individual country/region in our more disaggregated dataset. As an example, Cristea et al. (2013) report values for an aggregate region of Malaysia and Indonesia, which apply to both Malaysia and Indonesia in our data set. Assigning the Cristea et al. (2013) regions to our regions is relatively straight forward since both are based on the GTAP.[40]

Weight-to-value ratios are provided at the exporter-sector level in the Cristea et al. (2013) data. We assign the weight to value ratio for our electricity and other sectors to zero. Electricity is transmitted through powerlines, while the other sector is mainly services. To account for price level differences between the Cristea et al. (2013) data and our baseline, we adjust the weight to value ratios using the US implicit GDP deflator.

The Cristea et al. (2013) data does not include mode shares for intranational trade, but does include within region values for aggregated regions. We construct sectoral intranational mode shares from the Cristea et al. (2013) data in two ways. First, for countries in our data set that are in the aggregated regions in the Cristea et al. (2013) data, we use the modes shares for within region trade.[41] For example, we use within region mode shares for the Malaysia and Indonesia region in the Cristea et al. (2013) data for the intranational mode shares for both Malaysia and Indonesia in our data set. Second, for the individual countries in the Cristea et al. (2013) data, we use trade weighted averages of the mode shares across all contiguous countries.[42]

We adjust intranational mode shares for natural gas, crude and refined petroleum products to account for pipeline transport. We assume that domestic mode shares for natural gas, crude oil and refined petroleum are 0.95, 0.75 and 0.6 respectively, which are consistent with values for the US.[43] We assume that the emissions from pipeline transport are zero, which is consistent with Shapiro (2016).

[40] The Cristea et al. (2013) does not include values for central, western or eastern African countries. We use Sub-Saharan Africa values for these countries.

[41] The exception to this rule is Australia and New Zealand, which are an aggregated region.

[42] The exception to this that for African countries we use weighted average mode shares for within Africa trade.

[43] Petroleum mode shares are reported by the Bureau of Transportation Statistics. Virtually all natural gas is moved by pipeline.

A.2 Solution algorithm

Following Shapiro (2016) the model can be solved as a system of N equations (labor market clearing conditions) and N unknowns (proportional wage changes). Given $\hat{w}_i$, we use a contraction mapping on (13) and (14) to determine the proportional price changes. With the proportional changes in prices, we can solve for proportional changes in expenditures and income ($\hat{X}_j$, $\hat{X}_i^s$, $\hat{X}_i^{m,T}$ and $\hat{X}_{ij}^s$). To do so, we substitute Equation (15) into Equations (16), (17) and (18). This forms a linear system in $\hat{X}_j$, $\hat{X}_i^s$, $\hat{X}_i^{m,T}$ that can be solved using matrix algebra. With baseline values and proportional changes in expenditures and income we can evaluate the equilibrium condition (12).

A.3 Scale-Composition-Technique Decomposition

The trade and environment literature frequently decomposes changes in environmental impacts into scale, composition and technique effects (e.g., Copeland and Taylor (1994) or Cherniwchan et al. (2017)). Here we present this decomposition using our notation. 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 production emissions (excluding emissions from household consumption of fossil fuels) can be written as:

$$EP = \sum_j \sum_s k_j^s V_j^s \tag{A.1}$$

where k_j^s are the emissions per unit of value added and V_j^s is value added for sector s in country j. Although the emissions associated with the use of an input in a particular sector (k_j^{st}) are fixed, k_j^s are endogenously determined because they depend on these emissions factors, as well as value added and intermediate input shares.

Taking logs and differentiating, we obtain:

$$\frac{dEP}{EP} = \frac{dV}{V} + \sum_j \sum_s \frac{EP_j^s}{EP} \frac{d\left(V_j^s/V\right)}{\left(V_j^s/V\right)} + \sum_j \sum_s \frac{EP_j^s}{EP} \frac{dk_j^s}{k_j^s} \tag{A.2}$$

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.

A.4 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:

$$X_i^g \tilde{\kappa}_i^g = E_i^g + \sum_h \sum_f X_{hi}^{fg} \tilde{\kappa}_h^f \tag{A.3}$$

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.3) in matrix form and solve for $\tilde{\kappa}_i^g$.

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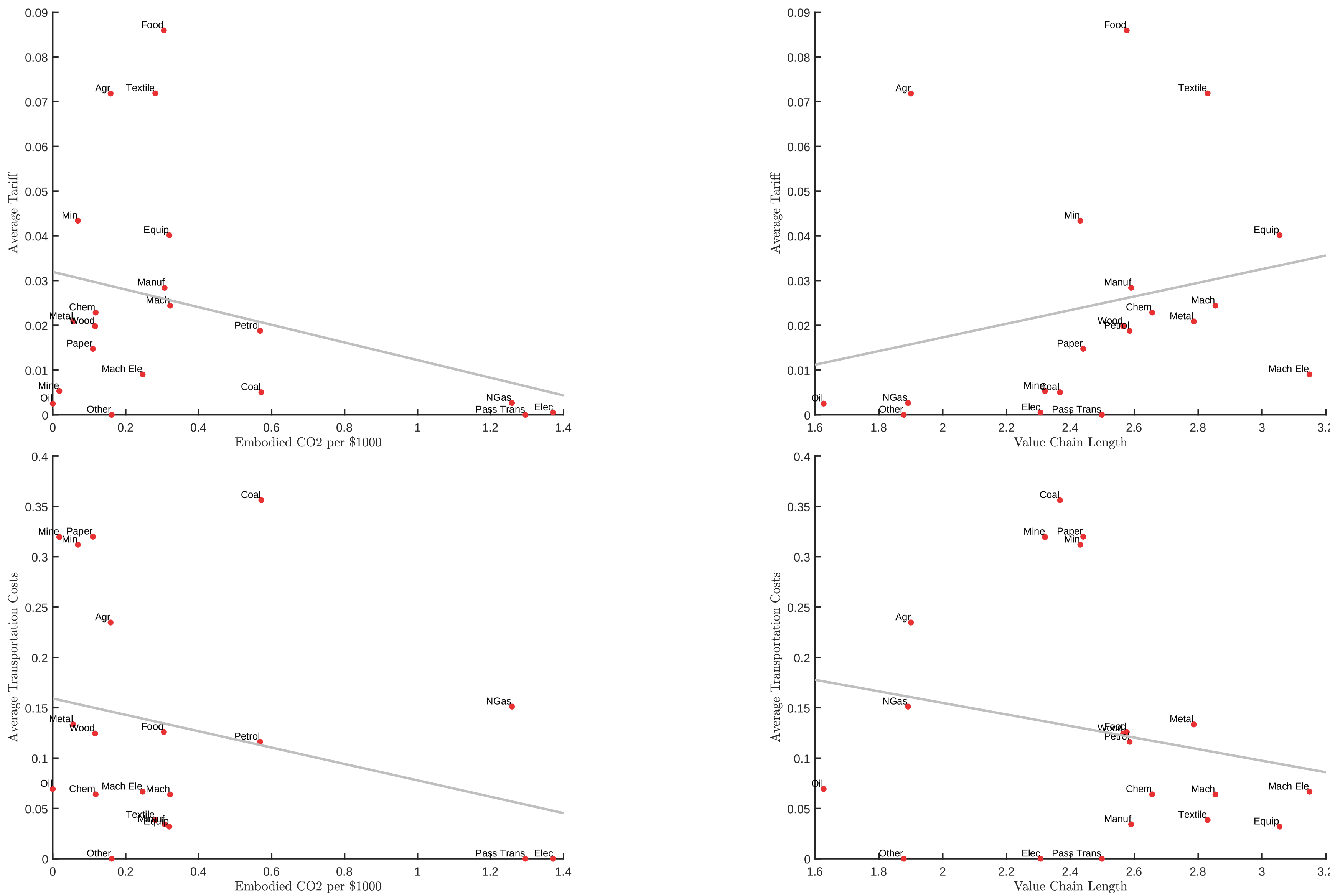

Notes: Points reflect sectoral average tariffs, transportation costs, embodied CO_2 emissions and value chain lengths. Average tariffs and transportation costs are weighted by sector output. Average embodied CO_2 and value chain lengths are weighted by final consumption. Embodied emissions and value chain length calculations are discussed in Sections A.4 and 2.4 respectively.

Figure A.1: Trade Barriers vs Embodied CO_2 and Value Chain Lengths

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.1: Regional Aggregation

	GTAP Sectors
Agr - Agriculture	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 products	Chemical,rubber,plastic prods
Coal - Coal	Coal
Elec - Electricity	Electricity
Equip - Equipment	Motor vehicles and parts; Transport equipment nec
Food - 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 nec	Machinery and equipment nec
Mach_Ele - Electronic equipment	Electronic equipment
Manuf - Manufactures nec	Manufactures nec
Metal - Metal products	Ferrous metals; Metals nec; Metal products
Min - Mineral products	Mineral products nec
Mine - Minerals	Minerals nec
NGas - Natural Gas	Gas; Gas manufacture, distribution
Oil - Oil	Oil
Other - Other	Water; Construction; Trade; Communication; Financial services nec; Insurance; Business services nec; Recreation and other services; PubAdmin/Defence/Health/Educat; Dwellings
Paper - Paper products	Paper products, publishing
Pass Trans - Passenger transport	Transport nec; Sea transport; Air transport
Petrol - Petroleum products	Petroleum, coal products
Textile - Textiles	Textiles; Wearing apparel; Leather products
Wood - Wood products	Wood products

Table A.2: Sector Aggregation

	tCO_2/1000$	kg/$	km/kg
Agriculture	0.22	2.01	6890.58
Chemical products	0.08	0.75	6412.06
Coal	0.51	8.91	7400.61
Electricity	0.00	0.00	-
Equipment	0.05	0.14	6588.99
Food	0.08	0.86	6198.75
Machinery nec	0.10	0.23	7236.01
Electronic equipment	0.13	0.14	7144.43
Manufactures nec	0.04	0.13	8386.58
Metal products	0.12	0.89	6025.96
Mineral products	0.16	1.76	5323.10
Minerals	0.63	7.94	10426.59
Natural Gas	0.31	5.41	4498.52
Oil	0.19	2.99	8014.59
Other	0.00	0.00	-
Petroleum products	0.17	3.05	5941.33
Paper products	0.14	1.21	5965.81
Textiles	0.05	0.13	7059.99
Passenger transport	0.00	0.00	-
Wood products	0.07	0.79	5415.15

Notes: The first column reports average emissions intensity (κ_{ij}^s) of international transport by sector at baseline trade flows. The kg/$ column reports average weight to value ratios (ξ_{is}^s in equation (9)) and the the km/kg column reports the average distance traveled per kilogram of good traded.

Table A.3: Emissions Intensity of International Transport by Sector

	GDP (billion \$)	Value (billion \$)	CO_2 (MT)		
			Using	Transport	Embodied
chn	6721.57	20859.43	8307.08	501.36	6840.85
usa	15029.80	28741.56	7207.99	2435.85	7418.23
ind	1744.49	3746.94	2087.23	122.42	2007.07
rus	1817.55	3817.47	1823.31	272.41	1524.28
jpn	5666.96	11633.84	1109.98	93.40	1482.87
deu	3370.59	6823.50	763.33	103.62	985.68
can	1725.43	3328.45	637.35	144.72	630.83
bra	2300.03	4388.54	616.97	271.33	610.81
kor	1060.44	2994.78	559.41	74.01	576.47
aus	1312.10	2708.77	551.59	166.60	454.28
irn	525.77	925.00	514.87	51.69	494.99
mex	1145.09	2045.46	490.58	47.60	538.10
sau	756.30	1222.32	483.36	126.44	414.93
gbr	2260.51	4363.29	451.67	30.56	705.94
idn	842.16	1697.83	415.70	44.58	437.75
ita	2056.62	4612.97	395.89	56.34	565.74
fra	2541.20	5291.87	375.50	84.53	593.36
zaf	381.53	934.95	368.26	38.41	266.54
kaz	186.79	450.93	327.97	20.62	189.77
tur	683.38	1463.51	323.69	23.62	403.15

Notes: Table reports GDP, gross output and total CO_2 emitted by the top 20 emitting countries. Using column allocates emissions according to the country in which the fossil fuels are used and includes fuels used by households and passenger transport sector. Transport column reports emissions from shipping goods allocated to the originating country. Embodied column allocates emissions according to final consumption. The top 20 countries comprise more than 80% of total CO_2, 78% of total embodied CO_2 and 78% of global GDP.

Table A.4: Emissions by Country

	Proport.	OECD	Non-OECD
Δ CO_2 (MT)	615.3	135.8	468.0
Product/Consump	316.6	37.1	274.1
Transport	298.7	98.7	193.8
Δ CO_2 (%)	1.80	0.40	1.37
Δ Q/V (%)	1.99	0.58	1.29
consumption shares	0.13	0.11	0.03
lengthening	1.84	0.46	1.26
Δ Q/V (%) - Leontief	1.04	0.31	0.63
consumption shares	0.13	0.10	0.03
lengthening	0.89	0.21	0.60
Δ Transport CO_2 (MT)	298.7	98.7	193.8
International	363.2	126.9	229.3
Domestic	-64.5	-28.2	-35.5
Δ Transport CO_2 per $ Gross Output (%)	2.76	0.98	1.82
kg/Q	-0.17	0.19	-0.32
kg-km/kg	8.17	2.41	5.69
ET/kg-km	-4.84	-1.58	-3.35
Δ International Transport CO_2 per $ Gross Output (%)	1.06	1.09	0.25
kg/Q	-0.64	-0.13	-0.37
kg-km/kg	2.20	0.92	1.37
ET/kg-km	-0.48	0.29	-0.74
Δ Production CO_2 (%)	1.22	0.16	1.03
Scale	0.50	0.19	0.31
Composition	0.06	0.41	-0.38
Technique	0.76	-0.45	1.20
Δ Production CO_2 (%) - Leontief	-0.51	-0.26	-0.26
Scale	0.46	0.18	0.29
Composition	-0.29	0.27	-0.57
Technique	-0.49	-0.71	0.21

Notes: First column displays results for the elimination of global tariffs. Final two columns report results from individually removing OECD and Non-OECD tariffs. The consumption shares and lengthening rows decompose the change in the average value chain length and the kg/Q, $kg-km/kg$ and $ET/kg-km$ rows decompose transportation (and international transportation) emissions intensity as described in Section 2.4. Scale, Composition and Technique rows decompose production emissions as described in Section A.3. Rows labeled Leontief report results using the Leontief version of the model.

Table A.5: Additional Decompositions – Removing Global Tariffs

	Proport.	OECD	Non-OECD
Δ CO_2 (MT)	954.8	231.4	698.6
Product/Consump	529.4	86.2	437.4
Transport	425.4	145.2	261.2
Δ CO_2 (%)	2.80	0.68	2.05
Δ Transport CO_2 per $ Value Added (%)	6.37	2.17	3.90
Q/V	4.54	1.35	2.90
shares	0.20	0.15	0.05
lengthening	4.28	1.19	2.83
ET/Q	1.75	0.80	0.97
Δ Production CO_2 (%)	2.03	0.36	1.64
L-M Fixed	-0.99	-0.34	-0.65
EV (% of GDP)	1.17	0.42	0.75
EV (billion $)	801.1	289.1	511.7
CO_2 Damage @ SCC=50 $/t (billion $)	47.74	11.57	34.93
CO_2 Damage @ SCC=200 $/t (billion $)	190.97	46.28	139.72
Change in Avg. Tariff Rate	-2.89	-1.04	-1.86

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

Table A.6: Decomposition of Impacts of Removing Global Tariffs and NTBs

	Projected	All Modes	Sea	Air	Road	Rail
Δ CO_2 (MT)	322.8	-14.1	58.5	-50.8	-21.9	2.7
Product/Consump	647.1	299.5	137.4	5.0	139.6	15.9
Transport	-324.3	-313.6	-78.9	-55.8	-161.5	-13.3
Δ CO_2 (%)	0.94	-0.04	0.17	-0.15	-0.06	0.01
Δ Q/V (%)	0.20	0.04	0.03	-0.00	0.00	0.00
consumption shares	-0.02	-0.01	0.01	-0.02	-0.01	-0.00
lengthening	0.22	0.05	0.03	0.01	0.01	0.00
Δ Q/V (%) - Leontief	-0.21	-0.20	-0.04	-0.05	-0.09	-0.01
consumption shares	-0.02	-0.02	0.01	-0.02	-0.01	-0.00
lengthening	-0.19	-0.18	-0.05	-0.04	-0.09	-0.01
Δ Transport CO_2 (MT)	-324.3	-313.6	-78.9	-55.8	-161.5	-13.3
International	48.2	-47.3	-45.9	-0.8	2.3	-0.7
Domestic	-372.4	-266.3	-33.1	-55.0	-163.8	-12.6
Δ Transport CO_2 per $ Gross Output (%)	-6.43	-5.90	-1.52	-1.08	-3.00	-0.25
kg/Q	2.52	-0.48	0.44	-0.29	-0.45	-0.05
kg-km/kg	22.38	4.60	3.78	0.53	0.36	0.05
ET/kg-km	-25.42	-9.60	-5.53	-1.31	-2.91	-0.25
Δ International Transport CO_2 per $ Gross Output (%)	-0.69	-2.88	-2.39	-0.46	0.06	-0.03
kg/Q	19.33	3.45	3.13	-0.16	0.58	0.08
kg-km/kg	11.21	1.38	2.26	0.19	-0.78	-0.08
ET/kg-km	-25.16	-7.40	-7.44	-0.49	0.27	-0.03
Δ Production CO_2 (%)	2.29	1.06	0.49	0.01	0.50	0.06
Scale	0.48	0.29	0.08	0.08	0.11	0.01
Composition	-0.27	-0.18	-0.04	-0.12	-0.03	0.00
Technique	2.08	0.96	0.45	0.04	0.42	0.05
Δ Production CO_2 (%) - Leontief	1.07	0.40	0.24	-0.09	0.21	0.03
Scale	0.48	0.28	0.08	0.08	0.11	0.01
Composition	-0.03	-0.10	0.02	-0.14	0.01	0.01
Technique	0.64	0.22	0.14	-0.03	0.09	0.02

Notes: First column reports impacts of plausible mode-specific improvements in fuel efficiency over ten years (16% for air; 22% for road; 10% for rail; 25% for sea). The remaining columns report impacts of a 10% improvement in transportation fuel efficiency (with associated fuel cost reductions), first to all modes then to each mode individually. The consumption shares and lengthening rows decompose the change in the average value chain length and the kg/Q, $kg-km/kg$ and $ET/kg-km$ rows decompose transportation (and international transportation) emissions intensity as described in Section 2.4. Scale, Composition and Technique rows decompose production emissions as described in Section A.3. Rows labeled Leontief report results using the Leontief version of the model.

Table A.7: Additional Decompositions – Transportation Efficiency Improvements

	Proport.	Fixed	Swiss	Peaks	Escalation
Δ CO_2 (MT)	252.2	525.2	61.3	46.6	41.7
Product/Consump	125.2	259.6	32.5	29.2	-4.4
Transport	127.0	265.6	28.8	17.4	46.1
Δ CO_2 (%)	0.74	1.54	0.18	0.14	0.12
Δ Q/V (%)	0.40	0.98	0.26	0.41	0.36
consumption shares	0.06	0.11	0.02	0.01	0.06
lengthening	0.34	0.86	0.24	0.40	0.30
Δ Q/V (%) - Leontief	0.11	0.41	0.11	0.23	0.22
consumption shares	0.06	0.10	0.02	0.01	0.06
lengthening	0.05	0.29	0.10	0.23	0.16
Δ Transport CO_2 (MT)	127.0	265.6	28.8	17.4	46.1
International	156.5	320.4	36.6	22.3	59.8
Domestic	-29.5	-54.8	-7.8	-4.9	-13.8
Δ Transport CO_2 per $ Gross Output (%)	1.60	3.47	0.01	-0.35	0.21
kg/Q	0.16	0.42	-0.19	-0.31	-0.13
kg-km/kg	3.56	7.08	0.86	0.51	1.29
ET/kg-km	-2.04	-3.78	-0.66	-0.55	-0.94
Δ International Transport CO_2 per $ Gross Output (%)	0.86	2.07	-0.41	-0.62	-0.41
kg/Q	-0.24	-0.20	-0.41	-0.39	-0.69
kg-km/kg	1.07	1.97	0.21	0.09	0.37
ET/kg-km	0.03	0.29	-0.21	-0.33	-0.09
Δ Production CO_2 (%)	0.45	0.99	0.10	0.10	-0.02
Scale	0.25	0.25	0.25	0.25	0.25
Composition	-0.19	-0.21	0.01	0.10	0.17
Technique	0.41	1.04	-0.13	-0.22	-0.43
Δ Production CO_2 (%) - Leontief	-0.27	-0.40	-0.16	-0.13	-0.22
Scale	0.24	0.24	0.23	0.23	0.24
Composition	-0.29	-0.40	-0.08	-0.00	0.05
Technique	-0.20	-0.16	-0.28	-0.29	-0.50

(a) Change in Real Income = 0.25%

	Proport.	Fixed	Swiss	Peaks	Escalation
Δ CO_2 (MT)	362.3	551.2	124.1	88.3	164.7
Product/Consump	180.8	273.7	63.1	44.7	52.5
Transport	181.4	277.4	61.0	43.6	112.2
Δ CO_2 (%)	1.06	1.61	0.36	0.26	0.48
Δ Q/V (%)	0.67	1.21	0.56	0.69	0.77
consumption shares	0.08	0.12	0.04	0.03	0.09
lengthening	0.58	1.08	0.53	0.66	0.67
Δ Q/V (%) - Leontief	0.24	0.58	0.28	0.39	0.47
consumption shares	0.08	0.12	0.04	0.03	0.09
lengthening	0.15	0.44	0.25	0.37	0.38
Δ Transport CO_2 (MT)	181.4	277.4	61.0	43.6	112.2
International	223.0	339.1	75.9	54.1	136.9
Domestic	-41.5	-61.7	-14.9	-10.5	-24.7
Δ Transport CO_2 per $ Gross Output (%)	2.20	3.33	0.17	-0.26	0.87
kg/Q	0.19	0.35	-0.31	-0.41	-0.15
kg-km/kg	5.06	7.87	1.81	1.35	2.84
ET/kg-km	-2.92	-4.54	-1.30	-1.18	-1.77
Δ International Transport CO_2 per $ Gross Output (%)	1.11	1.75	-0.50	-0.89	-0.60
kg/Q	-0.34	-0.12	-0.58	-0.59	-1.69
kg-km/kg	1.49	2.27	0.46	0.32	1.00
ET/kg-km	-0.04	-0.40	-0.38	-0.62	0.11
Δ Production CO_2 (%)	0.66	1.05	0.22	0.16	0.22
Scale	0.35	0.35	0.35	0.35	0.35
Composition	-0.21	-0.17	0.04	0.15	0.32
Technique	0.56	0.95	-0.14	-0.31	-0.45
Δ Production CO_2 (%) - Leontief	-0.36	-0.39	-0.24	-0.19	-0.24
Scale	0.34	0.34	0.33	0.32	0.34
Composition	-0.37	-0.42	-0.10	-0.01	0.11
Technique	-0.28	-0.22	-0.39	-0.41	-0.68

(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. The consumption shares and lengthening rows decompose the change in the average value chain length and the kg/Q, $kg - km/kg$ and $ET/kg - km$ rows decompose transportation (and international transportation) emissions intensity as described in Section 2.4. Scale, Composition and Technique rows decompose production emissions as described in Section A.3. Rows labeled Leontief report results using the Leontief version of the model.

Table A.8: Additional Decompositions – Liberalization Scenarios

	Proport.	Fixed	Swiss	Peaks	Escalation
Δ CO_2 (MT)	230.4	310.7	263.4	251.3	206.2
Product/Consump	114.4	176.8	128.7	110.9	72.3
Transport	116.1	133.9	134.7	140.4	133.9
Δ CO_2 (%)	0.67	0.91	0.77	0.74	0.60
Δ Transport CO_2 per $ Value Added (%)	1.84	2.30	1.95	2.04	2.02
Q/V	0.36	0.44	1.11	1.24	0.87
shares	0.06	0.04	0.08	0.09	0.09
lengthening	0.30	0.40	1.03	1.15	0.76
ET/Q	1.47	1.85	0.83	0.78	1.14
Δ Production CO_2 (%)	0.41	0.67	0.48	0.41	0.30
L-M Fixed	-0.25	-0.07	-0.39	-0.46	-0.25
EV (% of GDP)	0.23	0.09	0.45	0.46	0.36
EV (billion $)	156.1	58.3	307.5	314.7	246.7
CO_2 Damage @ SCC=50 $/t (billion $)	11.52	15.53	13.17	12.57	10.31
CO_2 Damage @ SCC=200 $/t (billion $)	46.09	62.14	52.69	50.26	41.25
Change in Avg. Tariff Rate	-1.20	-1.20	-1.20	-1.20	-1.20

Notes: Columns reflect each liberalization scenario when the policy parameter (proportional or fixed cuts, A, τ^{max} and B) is set to achieve a targeted change in baseline trade flow weighted average tariff.

Table A.9: Comparing Liberalization Scenarios at 50% Tariff Reduction

	OECD	nonOECD	USA
Agriculture	0.00	0.00	0.00
Chemical products	0.00	0.00	0.00
Coal	0.00	0.00	-
Electricity	0.00	0.00	-
Equipment	0.00	0.00	0.00
Food	0.00	0.00	0.00
Machinery nec	0.00	0.00	0.00
Electronic equipment	0.00	0.00	0.00
Manufactures nec	0.00	0.00	0.00
Metal products	0.00	0.00	0.00
Mineral products	0.00	0.00	0.00
Minerals	0.00	0.00	0.00
Natural Gas	0.33	0.33	-
Oil	0.00	0.00	0.00
Petroleum products	0.00	0.00	0.00
Paper products	0.00	0.00	0.00
Textiles	0.00	0.00	0.00
Wood products	0.00	0.00	0.00

(a) Sector

	OECD	nonOECD	USA
Agriculture	0.00	0.00	0.00
Chemical products	0.00	0.00	0.00
Coal	0.00	0.00	-
Electricity	0.50	0.00	-
Equipment	0.00	0.00	0.00
Food	1.00	0.00	1.00
Machinery nec	0.00	0.00	0.00
Electronic equipment	0.00	0.00	0.00
Manufactures nec	1.00	0.00	1.00
Metal products	0.00	0.13	0.00
Mineral products	0.00	0.00	0.00
Minerals	0.00	0.00	0.00
Natural Gas	0.00	0.59	-
Oil	0.00	0.00	0.00
Petroleum products	0.00	0.00	0.00
Paper products	0.00	0.00	0.00
Textiles	0.00	0.00	0.00
Wood products	1.00	0.00	1.00

(b) Sector, OECD

	OECD	nonOECD	USA
Agriculture	0.00	0.00	0.00
Chemical products	0.00	0.00	0.00
Coal	0.00	0.00	-
Electricity	0.53	0.00	-
Equipment	0.00	0.00	0.00
Food	1.00	0.00	1.00
Machinery nec	0.00	0.00	0.00
Electronic equipment	0.00	0.00	0.00
Manufactures nec	1.00	0.00	1.00
Metal products	0.00	0.15	0.00
Mineral products	0.00	0.00	0.00
Minerals	0.00	0.00	0.37
Natural Gas	0.00	0.59	-
Oil	0.00	0.00	0.00
Petroleum products	0.00	0.00	0.00
Paper products	0.00	0.00	0.51
Textiles	1.00	0.00	0.00
Wood products	0.07	0.00	1.00

(c) Sector, OECD-US

Notes: Values reflect proportional reduction in tariffs required to minimize total CO_2. Missing values represent sectors where pre-existing tariffs are zero. reducing tariff reductions are at the sector level at the global scale (a), for OECD and Non-OECD countries separately (b), and for the US, other OECD countries and Non-OECD countries separately (c).

Table A.10: CO_2 Minimizing Tariff Reductions

	Sector	Sector-OECD	Sector-OECD-US
Δ CO_2 (MT)	-0.3	-20.9	-22.4
Product/Consump	-0.4	-39.8	-50.0
Transport	0.1	18.8	27.6
Δ CO_2 (%)	-0.00	-0.06	-0.07
Δ Transport CO_2 per \$ Value Added (%)	0.00	0.29	0.43
Q/V	0.00	0.09	0.13
shares	0.00	0.01	0.04
lengthening	0.00	0.08	0.08
ET/Q	0.00	0.19	0.30
Δ Production CO_2 (%)	-0.00	-0.15	-0.19
L-M Fixed	-0.00	-0.21	-0.31
EV (% of GDP)	0.00	0.05	0.06
EV (billion \$)	0.1	34.6	42.1
CO_2 Damage @ SCC=50 \$/t (billion \$)	-0.01	-1.05	-1.12
CO_2 Damage @ SCC=200 \$/t (billion \$)	-0.05	-4.18	-4.49
Change in Avg. Tariff Rate	-0.00	-0.22	-0.33

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

Table A.11: Decomposition of Impacts of CO_2 Minimizing Tariff Reform

	China	Other
Agriculture	0.06	0.00
Chemical products	0.05	0.00
Coal	0.10	0.00
Electricity	0.00	0.00
Equipment	0.12	0.00
Food	0.08	0.00
Machinery nec	0.13	0.00
Electronic equipment	0.05	0.01
Manufactures nec	0.00	0.00
Metal products	0.09	0.06
Mineral products	0.07	0.00
Minerals	0.02	0.00
Natural Gas	0.00	0.00
Oil	0.10	0.00
Other	0.00	0.00
Petroleum products	0.08	0.00
Paper products	0.05	0.00
Textiles	0.02	0.00
Passenger transport	0.00	0.00
Wood products	0.09	0.00

(a) US Tariffs on Imports

	China	Other
Agriculture	0.17	0.00
Chemical products	0.07	0.00
Coal	0.25	0.01
Electricity	0.00	0.00
Equipment	0.21	0.00
Food	0.22	0.02
Machinery nec	0.07	0.00
Electronic equipment	0.05	0.00
Manufactures nec	0.08	0.00
Metal products	0.22	0.02
Mineral products	0.07	0.00
Minerals	0.08	0.00
Natural Gas	0.10	0.00
Oil	0.00	0.00
Other	0.00	0.00
Petroleum products	0.25	0.00
Paper products	0.13	0.01
Textiles	0.08	0.00
Passenger transport	0.00	0.00
Wood products	0.09	0.01

(b) Tariffs on US Exports

Notes: Table reports tariff changes used in the trade war counterfactual. Values reflect sector average changes in tariffs weighted by baseline value of trade flows. Tariff changes are from Amiti et al. (2019), who compile US import tariffs and retaliatory tariffs on US exports for 2017 and 2018 from a variety of national data sources. We calculate the additional tariff rates due to the trade war at the end of 2018. We aggregate these tariff rates from detailed industries (HTS6 and HTS10) to our GTAP sectors using the 2017 total value of imports/exports from the U.S. Census Bureau.

Table A.12: Changes in Tariffs due to 2018 Trade War